A Lunar Reference Mission for Advanced Life Support

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1 INTRODUCTION

This document outlines one possible Lunar Design Reference Mission (LDRM) for the Exploration Life Support (ELS) Project. When complete, this information will form a basis from which to add a LDRM to the current ELS Systems Integration, Modeling, and Analysis (SIMA) element's Reference Missions Document (Stafford, *et al.*, 2001). This document also provides an overall context and environment in terms of a reference mission for ELS Project technology assessments and system architecture analyses. This LDRM assumes a long-duration lunar mission as described by the "Lunar Architecture" in NASA's Exploration Systems Architecture Study (ESAS) report (ESAS, 2005).

Some values below are identified as "threshold" while others are "objective." This terminology arises from recent requirements developed by the Exploration Systems Mission Directorate (ESMD) of the National Aeronautics and Space Administration (NASA). Commonly, a "threshold value" is the minimum acceptable performance value for a particular system or vehicle. However, any additional performance up to the "objective value" would be desirable from NASA's perspective. *Unless specified otherwise, assume the objective values as default values for the missions below.*

The information here represents a finite number of options within a reference mission for life support analysis. This, however, is *not* an official reference mission of the National Aeronautics and Space Administration, nor should any portion be construed as such. Rather, SIMA intends to conduct technology and architecture studies to investigate possible life support design options using this document as a basis.

Finally, this manuscript should also *not* be construed as documenting a completed study that outlines life support systems for elements of NASA's proposed human lunar architecture. While it is intended that complete information for a high-level life support system concept is included, based upon current operational technologies, this is seen by SIMA as an *initial iteration* for ongoing life support system studies that will eventually examine many possible configurations and technologies before any recommendations of actual configurations are possible.

2 OVERALL MISSION ARCHITECTURE

The LDRM overall mission architecture, as envisioned for a long-duration lunar base, consists of three habitable elements (ESAS, 2005). The first vehicle, a Crew Exploration Vehicle (CEV), houses the crew from launch to the vicinity of Luna. A second vehicle, the Lunar Surface Access Module (LSAM), houses the crew from the orbiting CEV to the lunar surface. Once on the lunar surface, the Lunar Outpost (LO) provides the crew habitat for the surface mission. The LO, which is envisioned within ESAS (2005) as a multi-element facility, arrives on the lunar surface autonomously before the LSAM. Following the surface stay, the crew will use the LSAM to return to the CEV, and the CEV will house the crew from lunar orbit back to the Earth's surface. In the long-duration scenario envisioned within ESAS (2005) for the LO, this surface facility will, once emplaced, be occupied continuously and have a design lifetime not less than ten years.

2.1 LUNAR TRANSIT

Multiple elements provide propulsion for this architecture. Initially, the elements of the LO, including a long-duration crew habitat, a power system, other cargo, and a redundant LSAM [1], are emplaced autonomously on the surface of Luna. A Cargo Launch Vehicle (CaLV) [2] places each surface asset, which is integrated with an LSAM Descent Stage and an Earth Departure Stage (EDS), into low-Earth orbit (LEO). Each EDS inserts its surface payload, an asset integrated with an LSAM Descent Stage, into a transfer orbit for Luna. The EDS is discarded. The LSAM Descent Stage brakes the vehicle into a low-lunar orbit (LLO), and then lands on the lunar surface with its payload.

As noted above, the crew transports to Luna in two vehicles. The LSAM, integrated with an EDS, launches into LEO aboard a CaLV. Later, a Crew Launch Vehicle (CLV) [3] propels the CEV with a crew of four into LEO. After the CEV completes an Earth orbit rendezvous (EOR) with the LSAM-EDS stack, the EDS propels the combined vehicles towards Luna before it is discarded. The LSAM Descent Stage brakes the CEV-LSAM stack into a LLO. After the crew transfers to the LSAM, the LSAM undocks and the LSAM Descent Stage places the crew on Luna near the LO. At the conclusion of the surface mission, the LSAM Ascent Stage returns the crew to LLO and conducts a lunar orbit rendezvous (LOR) with the CEV. The CEV Service Module places the CEV into a transfer orbit to return to Earth. Just prior to re-entry, the CEV Service Module is discarded and the CEV Command Module, a capsule, returns the crew to the surface of Earth. This overall transportation approach is designated as the "1.5-Launch EOR-LOR Architecture" within ESAS (2005).

2.2 LUNAR SURFACE OPERATIONS

Lunar surface operations use two habitable elements, the LSAM and the crew habitat in the LO, along with one or more cargo vehicles. The cargo vehicles and the other LO elements transit to the lunar surface autonomously, landing within 100 m of each other. [4] The specific order of events is still under consideration, although a concept outlined in ESAS (2005) would appear to place on Luna, in order, a power supply, a crew habitat, a logistics lander, and a spare LSAM before the first crew arrives. The LO crew habitat will provide both an extended-duration habitat and an airlock, while the other LO elements will provide other surface infrastructure and expendables for nominal surface missions of up to 181 days per crew. The LSAM, which has a much smaller volume than the LO crew habitat, will ferry the crew from the CEV to a lunar surface location no more than 100 m from the LO crew habitat. At the end of each crew's surface stay, an LSAM will ferry the crew back to the waiting CEV (ESAS, 2005).

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[1] As implied by ESAS (2005), the redundant LSAM provides an additional means for the crew to leave Luna if, for some reason, one LSAM fails to function properly prior to departure. As envisioned, each crew will bring an LSAM when they arrive, but they will nominally depart in the LSAM emplaced or brought by the previous crew.

[2] The CaLV has a projected payload capacity to LEO of 125 metric tons based on ESAS (2005).

[3] The CLV has a projected payload capacity to place a CEV in LEO. Based on overall mass estimates for CEV in ESAS (2005), this payload capacity is at least 23 metric tons.

[4] According to Constellation documents, landing accuracy for LSAM is 1 km without surface aides and 100 m with surface aides. The first LO element should carry a landing aide so the accuracy for subsequent elements should be within 100 m of the first element.

2.3 MISSION CONCEPTS FOR ANALYSIS

The LO 181-day surface mission may represent either of at least two possible scenarios. One mission is an extended duration base at either a Lunar Pole or the Lunar Equator. The other is a rehearsal for an exploration mission to Mars at either a Lunar Pole or the Lunar Equator.

2.3.1 PERMANENT LUNAR BASE

One possible mission profile is an extended mission in a previously emplaced LO. For this case, an earlier crew visited the LO site and initially activated the facility. Thus, the current crew is responsible only for stowage of their own mission equipment and consumables, either transferred from the LSAM in which they arrived, and/or from separate, autonomously-landed cargo vehicles whose sole purpose is resupply. [5] For this scenario, assume the LO is occupied continuously by two crews per year (ESAS, 2005). Further, assume the LO active lifetime is at least 10 years (ESAS, 2005). The total number of crews is currently undefined (ESAS, 2005).

One possible example of this first scenario is illustrated here. The initial mission will be 42 days in duration.[6] In addition to using the LO as a primary habitat during their surface stay, the first crew will also complete all initial activation duties within and around the LO. This crew may also provide initial site assessments from which scientific mission objectives for following crews will be defined. Assuming twenty-one crews total for the active life of the LO, the second through twenty-first crews will nominally conduct 181-day exploration missions using the same LO as a primary habitat. [7] The actual mission duration may vary to allow flight operations shortly after local sunrise to reduce landing hazards for the incoming crew. [8] Each crew will overlap with the previous crew 8 days. [9] Assuming a flight rate of approximately two visits per year, this LO will be occupied by one crew for 3,595 days plus 168 days with two crews for a total duration of just over ten years. The actual dormant lifetime of the LO from its landing until the first crew arrives is currently undefined. A reasonable assumption is that this duration is no more than 45 days. [10] Assume the LO crew habitat will be powered and fully pressurized during dormancy.

2.3.2 MARTIAN EXPLORATION MISSION REHEARSAL

A second possible mission profile simulates, on the lunar surface, an initial martian mission. As noted in the rationale for CTS0610C (Lembeck, 2005a), an opposition-class martian mission permits surface operations on Mars of 30 to 90 days, depending upon the propulsion technology employed and the geometry of the planetary alignment at the time of the mission. To simulate a rehearsal for an opposition-class mission to Mars on Luna, a LO lands autonomously prior to the crew. As appropriate, the LO systems activate autonomously, although the crew may have some initial activation duties. Overall, the crew conducts a single 101-day exploration mission on Luna using the LO as their primary habitat. [11] Following completion of the mission, the LO would be abandoned. [12] Although the actual dormant vehicle lifetime from launch until the crew arrives is currently undefined, a reasonable duration is no more than 45 days following initial LO landing for this scenario. [13, 14]

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5 Additional cargo vehicles may provide resupply for each additional crew, but these details are currently undefined.

6 A duration of 42 days provides the crew with two complete lunar days and one complete lunar night on Luna.

7 ESAS (2005) stipulates a minimum design life for a Lunar Outpost of not less than ten years. This scenario is consistent with a 10-year facility life, although longer-duration facilities are possible and even likely.

8 Shortly before local sunset may be another possible arrival time. During Apollo, crews arrived on Luna shortly after local sunrise (1) to minimize environmental thermal loads since the Lunar Module rejected heat via evaporation of a limited supply of water and (2) to mark landing hazards using long shadows cast by possible obstructions when the Sun is close to the local horizon.

9 An estimate based on current practice for International Space Station (Lewis and Shkedi, 2006).

10 This is an estimate based on an earlier study, Robertson and Geffre (2004).

11 A 101-day mission corresponds to four complete lunar days and three complete lunar nights.

12 While this LO may be reoccupied for subsequent missions, for sizing purposes under this scenario assume the vehicle is abandoned in-place after the initial mission.

13 This is an estimate based on Robertson and Geffre (2004). Actual mission timelines are currently undefined.

14 For an actual martian mission, the LO dormancy duration prior to the arrival of a crew may be on the order of two years plus the duration for the LO to transit from Earth to Mars. This estimate is consistent with a mission architecture that transfers autonomous surface assets to Mars on the transit opportunity before the initial crew to

2.4 Overall Mission Definition

The following paragraphs apply to the entire architecture of this LDRM, as appropriate.

2.4.1 Surface Site

During the period known as the "Lunar Base and Mars Testbed," lunar missions may land anywhere on the lunar surface (CTS0430G, Lembeck, 2005a, [15] and ESAS, 2005) using only the LSAM. However, extended-duration missions that use a LO will be restricted to polar or equatorial sites (CTS0450G and CTS0610C, Lembeck, 2005a, and ESAS, 2005).

2.4.2 Crew Size

For this mission, the crew size is 4 crewmembers (ESAS, 2005). [16]

2.4.3 Crewmember Characteristics

In the text that follows, it is assumed here that a design crewmember is male, has a body mass of 98.5 kg, and requires 14.40 MJ/CM-d of metabolic energy to support his mass during nominal intra-vehicular activities. [17] While the preceding values provide an upper bound, each vehicle design should also accommodate female crewmembers with a body mass of 41.0 kg and a daily metabolic energy intake of 7.95 MJ/CM-d. [18] Assume crewmembers are older than 30 years. [19] See Lane, *et al.* (1996) for details. [20] For extravehicular activities, Lane, *et al.* (1996) stipulates an additional 2.09 MJ/CM-d to support the added exertion.

2.4.4 Crew Survival

Space systems shall be designed so that no two failures result in crew or passenger fatality or permanent disability (34419, HRRSS, 2005).

2.4.5 Mission Success

The vehicles within the lunar architecture shall generally provide at least single failure tolerance to loss of mission and critical hazards. See CTS0030H (Lembeck, 2005a) for details and exceptions.

2.5 Environmental Properties

The environment is a significant factor in spaceflight, and it drives certain aspects of the overall design. For the current LDRM, the vehicles involved will experience several different environments. All vehicles will experience a LEO environment, an Earth-Luna transit environment, and a LLO environment. Additionally, the LSAM and LO will experience a lunar surface environment either near the Lunar Equator or a Lunar Pole (CTS0610C, Lembeck, 2005a, and ESAS, 2005).

2.5.1 Location

For this LDRM, the LSAM and LO will land near either a Lunar Pole or the Lunar Equator (CTS0610C, Lembeck, 2005a, and ESAS, 2005). The CEV will remain dormant in LLO during the surface mission (CEV0485C, Lembeck, 2005a, and ESAS, 2005).

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assure safe surface access and autonomous surface operation at Mars by the LO. Opportunities to transfer to Mars using the least energetic orbit occur about once every 26 months.

15 Literature citations of this form have three fields for information instead of just two. Field one lists a specific requirement number. Field two is the document author or the document acronym. Finally, field three is the document date. In this form, information in the second and third fields identifies specific references in Section 7.

16 CTS0017G (Lembeck, 2005a) specifies a threshold crew size of 1, 2, 3, and 4 crewmembers, with an objective crew size is 5 and 6 crewmembers.

17 These values correspond to a 95th-percentile male based on selection guidelines for NASA's Astronaut Corps.

18 These values correspond to a 5th-percentile female crewmember, based on selection guidelines for NASA's Astronaut Corps. The vehicle design should not preclude use by any combination of potential NASA astronauts.

19 While crewmembers younger than 30 years old are possible, historically, most NASA astronauts are at least 30 years old by the time they fly in space.

20 Table 3.3.6 of BVAD (2004) carries similar information.

2.5.2 ENVIRONMENTAL LIGHTING

2.5.2.1 LUNAR EQUATOR

The average sol on Luna is 29.5300 ± 0.0012 terrestrial Solar days [21] (Weast and Astle, 1979).

2.5.2.2 LUNAR POLE

Although similar to sites at the Lunar Equator with regard to the overall length of a sol, overall lighting differs at a Lunar Pole. Luna's axis of rotation is inclined only 1.5° with respect to the ecliptic plane (Fender and Trosper, 2004), so seasonal variations are minimal and the Polar Regions annually receive more hours of light than at the Lunar Equator. Bussey, *et al.* (2004) studied local illumination at the lunar poles using data from Clementine. Their research indicates that at least two locations exist at the South Lunar Pole that are illuminated at least 70% of the time. [22] There may be up to four sites at the North Lunar Pole that are illuminated continuously, but the Clementine data was insufficient to verify this hypothesis. Thus, assuming a LO base is emplaced at either site, then no more than about 212.6 h out of every 708.7 h will be dark.

2.5.3 EXTERNAL THERMAL ENVIRONMENT

2.5.3.1 COMMON PARAMETERS IN NEAR-EARTH SPACE

Space has an average temperature of 3 K. The incident solar radiation averages 1.367 kW/m². The maximum solar flux, at Earth's perihelion [23], is 1.414 kW/m², while the minimum solar flux, at Earth's aphelion [24], is 1.322 kW/m². The Sun may be treated as a blackbody at a characteristic temperature of 5,777 K. See NEDD (2005) for details.

The natural incident energy balance in near-Earth space, in general, is the sum of direct solar flux, the albedo or reflected solar flux, and an infrared flux. A direct solar flux applies whenever a vehicle is in direct sunlight, either in space, in orbit, or on Luna. Albedo applies whenever a vehicle is in direct sunlight and adjacent to a planetary body. When in orbit, the albedo is reflected sunlight from the planetary body below. When on the surface, the albedo is reflected sunlight from the surface of the planetary body. An infrared flux also applies whenever a vehicle is adjacent to a planetary body due to the absolute temperature of that planetary body. When in orbit, the infrared flux is related to the effective blackbody surface temperature of the planetary body below. When on the surface, the infrared flux is related to the temperature of the surface regolith.

2.5.3.2 LOW-EARTH ORBIT

Albedo radiation in LEO varies according to surface topography, cloud cover, and solar zenith angle, although this reflected radiation has almost the same spectral quality as direct solar radiation. See NEDD (2005) for complete albedo variation. For simple thermal energy balances, an average albedo value is 0.306 (Williams, 2004).

NEDD (2005) recommends representing the outgoing long-wave radiation (OLR) [25] from Earth as a diffuse, gray surface corresponding to a temperature between 250 K and 300 K. An older NASA environmental document, Anderson and Smith (1994), recommends an average blackbody radiant temperature of 288 K to represent OLR emission from Earth. Again, OLR emission varies according to surface topography and cloud cover, but its variation is less than for albedo.

2.5.3.3 EARTH-LUNA TRANSIT ENVIRONMENT

The natural energy balance during Earth-Luna transit is described by parameters listed specifically elsewhere in this document. In this case, the local natural energy balance, including any surface temperature, depends only on solar flux, spacecraft orientation, and spacecraft surface properties.

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21 Or, equivalently, this is 708.720 ± 0.029 hours.
22 Interestingly, these two sites are located on a common ridge line on the rim of Shackleton Crater and are physically about 10 km apart; taken together, these two sites are illuminated 98% of the time.
23 This coincides with the winter solstice as defined for the Northern Hemisphere.
24 This coincides with the summer solstice as defined for the Northern Hemisphere.
25 OLR is sometimes called infrared radiation (IR).

The Earth-Luna transit environment applies when a vehicle is sufficiently far from Earth. Here it is assumed that thermal loads experienced while transitioning from the LEO environment to the true Earth-Luna transit environment will not define sizing for any spacecraft systems. However, for a mature spacecraft design this assumption should be tested.

2.5.3.4 Low-Lunar Orbit

At Luna, the incident solar radiation again averages 1.367 kW/m². However, because Luna can be up to 405,504 km either closer to or farther from the Sun, the maximum solar flux is 1.422 kW/m², while the minimum solar flux is 1.315 kW/m². The Sun may be treated as a blackbody at a characteristic temperature of 5,777 K. See NEDD (2005) for details.

According to Smith and West (1983), the lunar surface temperature varies between 102 K just before sunrise up to 384 K at local noon. Lunar regolith, as a first approximation, may be treated as a blackbody emitting at its current temperature. Luna has an average bolometric normal albedo of 0.12 on the near side, and a value of 0.15 on the far side (NEDD, 2005). [26] On the near-side, the albedo varies locally from 0.07 up to 0.20 (NEDD, 2005).

For completeness, LLO is a circular orbit at 100 km (54 nmi) above the lunar surface.

2.5.3.5 Lunar Equator

According to Smith and West (1983), the lunar surface temperature varies between 102 K just before sunrise up to 384 K at local noon. [27] Lunar regolith, as a first approximation, may be treated as a blackbody emitting at its current temperature. For the lunar surface, the effective emissivity is 0.92 and the effective absorptivity is 0.93 (Rickman, 2004). For a mare, the albedo may be as low as 0.067 [28] (Smith and West, 1983), although higher values, up to 0.20, are appropriate locally for highland terrain. Based on Rickman (2004), the lunar regolith has a thermal conductivity of 0.00201 W/(m●K), a density of 2,000 kg/m³, and a heat capacity between 251 J/(kg●K) and 829 J/(kg●K).

2.5.3.6 Lunar Pole

Though similar to Lunar Equator sites with regard to surface properties, surface temperatures differ at a Lunar Pole. The incident solar flux will be less severe because the Sun will remain no more than just above the horizon. Near a Lunar Pole, surface temperatures vary between 213 K and 233 K for regions permanently in sunlight (Bussey, *et al.*, 2004) according to models, although surface temperatures may fall to below 100 K in perpetual shadows (Fristad, *et al.*, 2004). According to Bussey, *et al.* (2004), craters in permanent shadow exist near both Lunar Poles and, based on data from Clementine and Lunar Prospector, craters near both Lunar Poles may support ice deposits.

2.5.4 Environmental In-Situ Resources

2.5.4.1 In Orbit or Transit

Vehicles in orbit or in transit have access to solar radiation and vacuum.

2.5.4.2 On the Lunar Surface

In addition to solar radiation and vacuum, vehicles on the lunar surface may also access oxides of metals and transition metals within the regolith in varying quantities. According to Smith and West (1983), on average, oxygen represents 61.0% of the elemental mass in lunar surface regolith, followed by 16.3% silicon, 9.5% aluminum, 4.3% magnesium, and 2.3% iron, plus lesser, yet measurable, quantities of sodium, calcium, potassium, titanium, and a few other elements. Elemental hydrogen, which is believed to be deposited by the solar wind, is also present in minute quantities. Actual availability of specific elements varies by site.

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[26] Per NEDD (2005), the lunar far-side has a greater proportion of relatively bright highland terrain compared to the near-side with its numerous darker maria.

[27] LS (1991), according to Fristad, *et al.* (2004), gives comparable temperatures at the Lunar Equator from 123 K to 373 K.

[28] This albedo implies a surface absorptivity of 0.933, which is consistent with the value from Rickman (2004).

Additionally, a hydrogen signal at the Lunar Poles from Lunar Prospector and Clementine data may indicate the presence of water ice in some perpetually dark craters (Fristad, *et al.*, 2004), but the existence, relative abundance, and ease of extraction of any water all remain topics for further investigation.

2.6 VALUES ASSUMED BY THE EXPLORATION LIFE SUPPORT RESEARCH AND TECHNOLOGY DEVELOPMENT METRIC

The Exploration Life Support Research and Technology Development Metric, or the Metric, calculation for the LDRM uses the following assumptions [29]:

- The Metric LDRM assumes the second mission profile in Section 2.3.2, which is a rehearsal for an opposition-class mission to Mars on Luna.
- All mission vehicles support a crew of four crewmembers.
- The overall duration on Luna is 101 days. Thus, to be consistent, the CEV will remain dormant in LLO for 102 days.
- The LO and LSAM land at the Lunar South Pole. [30]
- Each crewmember receives 2.5 kg/CM-d of potable water for dietary consumption.
- During transit each crewmember also receives 0.5 kg/CM-d of potable water for hygiene. On the lunar surface, this increases to 2.0 kg/CM-d of potable water for personal hygiene aboard LSAM and up to 5.45 kg/CM-d of potable water for personal hygiene aboard LO.
- Contingency beyond nominal mission durations are excluded for this calculation.

The Metric calculation for the LDRM uses all values defined by both the requirements and assumptions except as explicitly listed above. When a range is provided, the nominal value at the midpoint of the range is the default value unless specified otherwise above.

[29] While the form of the Exploration Life Support Research and Technology Development Metric for Fiscal Year 2006 and beyond is still under consideration, the values here are meant to support the annual metric process. Thus, what follows are the current estimates of parametric values for computing future Metric values.

[30] Constellation documents specify that the LO be located within 5 degrees of the Lunar South Pole.

3 Crew Exploration Vehicle for the Lunar Reference Mission

The emphasis in this section is on an element of the crew transit infrastructure, the Crew Exploration Vehicle (CEV). The CEV will transfer the crew from the surface of Earth to LLO, and from LLO back to the surface of Earth. The CEV will remain dormant in LLO while the crew conducts surface operations on Luna.

3.1 Applicable Requirements Associated with the Crew Exploration Vehicle Life Support System

The following criteria are discovered, as noted, in NASA documentation. Some values are derived from requirements while others are not. All, however, are mission-specific design decisions for this particular vehicle in this particular mission. Those subsystems that are not defined completely by mission-specific design decisions are specified more completely within the system based upon current operational technology in Section 3.2 below.

3.1.1 Mission Duration

The minimum CEV mission duration is described by several requirements. The CEV will transit from Earth orbit to lunar orbit in no more than 5 days (CTS0297G, Lembeck, 2005a). To support the surface mission in the LO, the CEV must loiter dormant in lunar orbit for a threshold of 43 days (CEV0485C, Lembeck, 2005a), up to an objective of 182 days (ESAS, 2005). Finally, the CEV will return from lunar orbit to Earth orbit in no more than 5 days (CEV0530G and CEV0315G, Lembeck, 2005a, and ESAS, 2005). Although there is no specific requirement yet, additional time may be added to the nominal CEV schedule for loiter in LEO prior to trans-lunar injection, or loiter in LLO prior to trans-Earth injection. Overall, the CEV is nominally inhabited by the crew for 13.25 days (ESAS, 2005) with an additional dormancy duration of 43 days, threshold, and 182 days, objective. Constellation documents specify that CEV is inhabited for a maximum of 18 days. [31]

3.1.2 Capacity

For this mission, the crew size is 4 crewmembers (ESAS, 2005), for 13.25 days, inhabited, plus 43 days to 182 days, dormant, in LLO as described above.

3.1.3 Air Subsystem

To support the overall mission, the CEV cabin atmosphere will operate at two nominal values. The higher pressure setting, to be compatible with local terrestrial pressure at launch, is 101.3 kPa ± 1.4 kPa (14.7 psia ± 0.2 psia) with an oxygen (O_2) partial pressure of 21.3 kPa ± 0.028 kPa (21.0% ± 2.0%). The lower pressure setting, to be compatible with LSAM, is 70.3 kPa ± 1.4 kPa (10.2 psia ± 0.2 psia) with an O_2 partial pressure of 18.6 kPa ± 0.028 kPa (26.5% ± 2.0%). See EAWG (2006). From Constellation requirements, the overall pressure for CEV must fall between 55 kPa (8.0 psia) and 117 kPa (17.0 psia). The diluent gas will be nitrogen (N_2). [32] The maximum allowable partial pressure of carbon dioxide during nominal operations is 0.71 kPa (0.103 psia) from Constellation requirements. The minimum oxygen partial pressure is 16.0 kPa (2.32 psia). To support docking with other spacecraft, such as the International Space Station (ISS), the CEV should also support cabin pressures up to 117 kPa (17.0 psia). Because CEV may dock with a variety of vehicles, it should support cabin atmospheric pressures and compositions anywhere between these limiting values.

Nominally, according to Constellation requirements, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s).

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[31] Implied by Constellation documents; CEV requires 72 CM-d for sizing potable water and other consumables.

[32] Alternate diluent gases or gas mixtures could be used. Nitrogen is assumed in Robertson and Geffre (2004), although it is not, to date, required by either human physiology or NASA requirements.

3.1.4 Habitation Subsystem

The crew shall be able to perform hand and body washing according to Constellation requirements. The crew shall have clothing.

3.1.5 Waste Subsystem

The crew will generate wet and dry trash. According to Constellation requirements, the vehicle should provide odor control, stowage, and accessible trash collection for the Waste Subsystem. To support urination, the Waste Subsystem shall provide disposal of associated consumable wipe materials, collect 0.118 m^3 of urine per flight [33], collect up to six urine discharges per hour, that may be up to 0.001 m^3/discharge. To support fecal discharge, the Waste Subsystem shall provide disposal of associated consumable wipe materials, collect 0.150 kg/CM-d and 0.000150 m^3/CM-d of fecal matter, collect up to 0.008 m^3/CM/mission of diarrheal discharge, which may be discharged as 0.004 m^3/CM-d of diarrhea or 0.002 m^3/discharge event. Further, to meet anticipated future waste requirements derived from planetary protection requirements and treaties (UN, 1967), untreated human metabolic wastes should not be allowed to impact planetary bodies besides Earth.

3.1.6 Water Subsystem

For CEV, based on Constellation requirements, the crew shall have 2.5 kg/CM-d of potable water, at a specified water quality during the nominal mission. For all purposes, cold water shall be 279.0 K ± 1.4 K (42.5 °F ± 2.5 °F), and hot water shall be 347.0 K ± 5.6 K (165 °F ± 10 °F). Further, to support re-entry countermeasures, the crew shall have an additional 1 kg/CM. Following landing, 4.5 kg/CM of potable water shall be provided.

Hygiene accommodations may also impact the Water Subsystem. The crew shall have 0.5 kg/CM-d for personal hygiene by Constellation requirements. Water for body cleansing shall be 310.9 K ± 8.3 K (100 °F ± 15 °F). [34] While Constellation requirements assume the crew shall have clothing, there is no requirement to launder clothing.

3.1.7 Extravehicular Activity Support External Interface

CEV0320H (Lembeck, 2005a) stipulates that CEV shall support EVA as a contingency. [35] Further, ESS0700 (Lembeck, 2005b) stipulates that nominal assembly operations, including docking or mating of two mission elements, shall not require crew EVA for success. Thus, the nominal mission profile will not conduct EVA from CEV.

3.1.7.1 Airlock

If EVA is necessary as a contingency, it is assumed that the entire crew will don extravehicular mobility units simultaneously and the entire cabin will be depressed. Thus, no airlock is necessary.

3.1.7.2 Frequency of Extravehicular Activities

Because EVA is a contingency mode for CEV, no nominal EVA frequency is specified. Overall EVA duration will be less than the duration of the as-yet-undefined contingency EVA hardware. [36]

3.1.8 Food External Interface

The Food Subsystem is not currently defined. However, by Constellation requirements, the vehicle shall prevent cross-contamination between food preparation and personal hygiene areas, and between food preparation and body waste management areas. Food shall be rehydrated with hot or cold

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[33] Constellation requirements stipulate collecting a volume of urine per crewmember in liters, $V_U = 3 + 2t$, where t is the mission duration in days. Assuming four crewmembers and a mission duration of 13.25 days, the overall urine volume is 118 liters, or 0.118 m^3.

[34] While Constellation documents require water at 310.9 K ± 8.3 K for body cleansing, it does not prohibit combining other cold and hot potable water streams to generate the specified stream.

[35] Supporting text further indicates that this requirement may be omitted if further study fails to identify contingency situations where an EVA capability is beneficial.

[36] Some sources suggest that contingency EVA from CEV might be conducted using launch / entry suits, which are pressurized, with umbilical lines that allow necessary translation from CEV to whatever vehicle is the crew's destination during this contingency mode.

potable water. Finally, the vehicle should allow the crew to prepare a meal for all crewmembers within a single 30-minute period.

3.1.9 POWER EXTERNAL INTERFACE

The power utility architecture is not fully specified at this time. However, the power utility will nominally supply 4.5 kW_e to the CEV while it actively houses the crew, with a maximum-duration-independent load of 6.0 kW_e (ESAS, 2005). The peak load, only for very short durations, may be up to 8.0 kW_e (ESAS, 2005). These power levels should not be viewed as limiting. Rather, these values underlie assumptions used to size the Power External Interface architecture described in Section 3.2.9.

3.1.10 THERMAL EXTERNAL INTERFACE

The Thermal External Interface architecture is not fully defined to date. The thermal load is the sum of the hardware heat loads [37], plus the crew metabolic heat load, plus any environmental loads. [38] To account for the cabin heat load and waste heat generation associated with the power system, the Thermal External Interface is sized to reject 6.25 kW_{th} (ESAS, 2005). More specifically, 5.0 kW_{th} is collected by internal cold plates, 0.75 kW_{th} is collected by a cabin heat exchanger, and 0.5 kW_{th} is collected by external cold plates (ESAS, 2005). As listed above, by Constellation requirements, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s).

3.2 CREW EXPLORATION VEHICLE LIFE SUPPORT SYSTEM ARCHITECTURE USING CURRENT TECHNOLOGIES

A CEV life support system architecture using current operational technologies is presented below to provide an initial overall design for analysts and system developers. The approach below might be viewed as a "baseline" for trade studies, but it certainly is *not* an optimized or officially recommended approach for a life support system within CEV.

The cabin atmosphere is maintained with high-pressure gas stores and consumable contaminant removal hardware. Clean water is provided from stores, while wastes are also stored. Food is pre-packaged, requiring only minor operations before consumption. The thermal management architecture relies on coldplates, heat exchangers, single-phase flow loops, and radiators and expendable heat rejection devices. See Figure 3.1. Note that while Figure 3.1 presents pictorially a single-string life support system, this is merely for "artistic clarity" and is not meant to imply that CEV will use a single-string life support system in practice. (Acronyms used in Figure 3.1 are listed in Section 8.)

3.2.1 AIR SUBSYSTEM

The air suite for the CEV with current technologies uses non-regenerable carbon dioxide (CO_2) removal equipment based on lithium hydroxide (LiOH). The trace contaminant control system (TCCS) for atmospheric gases uses activated carbon for non-combustible trace gas removal, and high efficiency particulate air (HEPA) filters for bacteria and particulate removal, neither of which are regenerated. Further, the TCCS also removes trace combustible gases from the crew cabin. Oxygen (O_2) and nitrogen (N_2) are supplied as pressurized gases from high-pressure (HP) stores. A major constituent analyzer (MCA) and a fire detection and suppression (FDS) system monitor for air contaminants and combustion products. The cabin atmospheric leakage rate is no greater than 0.15 kg/d (ESAS, 2005).

3.2.2 HABITATION SUBSYSTEM

The CEV life support architecture using current technologies assumes all clothing is brought pre-packaged from Earth at a rate of 0.46 kg/CM-d (ESAS, 2005) and used clothing is sent to the Waste Subsystem when it is no longer fit to wear. Disposable wipes at a rate of 0.15 kg/CM-d (ESAS, 2005)

[37] When unavailable, as a first approximation, the hardware heat load discharged for the thermal external interface to remove may be taken as equal to its input power. Note that because other heat rejection routes and chemical reaction kinetics, this assumption may be conservative.

[38] Environmental loads are unique to each vehicle; net environmental loads are normally small or zero when considered over the entire vehicle. Until a value is defined for CEV, assume net environmental loads are zero.

provide the crew with body cleansing and housekeeping support. Additionally, ESAS (2005) provides 5 kg/CM for recreational supplies and 2.3 kg/CM for sleep accommodations.

3.2.3 WASTE SUBSYSTEM

The Waste Subsystem provides only rudimentary collection and storage of waste products. The waste suite includes a toilet, pretreatment to stabilize urine, and separate storage volumes for human liquid and solid metabolic wastes and trash. Human liquid and solid metabolic wastes will return with the crew.

3.2.4 WATER SUBSYSTEM

The CEV Water Subsystem using current technologies provides water from stores. A process control water quality monitor samples dispensed water to assure overall water safety.

3.2.5 CREW EXTERNAL INTERFACE

See Section 2.4.3 for a description of crewmembers.

3.2.6 EXTRAVEHICULAR ACTIVITY SUPPORT EXTERNAL INTERFACE

Because EVA is only for contingencies from CEV, appropriate life support commodities are provided through an interface with the main life support storage caches. To be fully compatible with EVA hardware, the interface may pressurize some commodities before charging EVA hardware. For purposes of this LDRM, EVA will provide any specialized hardware to convey commodities to EVA hardware, while life support will provide only commodities.

3.2.7 FOOD EXTERNAL INTERFACE

Food is provided as individual entrées in the CEV architecture using current technologies. This diet relies on a variety of ambient-temperature storage (AS) foods. For the design case, this approach supplies 14.40 MJ/CM-d of metabolic energy for intravehicular activities. Employing Levri (2003) and assuming the Shuttle Training Menu as the applicable basis, the design-case metabolic energy corresponds to 1.397 kg/CM-d of food overall. The food mass, as-shipped, is 0.592 kg/CM-d moisture, or 42%, and 0.805 kg/CM-d dry food. An additional 0.321 kg/CM-d of disposable packaging directly protects the food, and specialized food-storage structure, or locker, adds an additional 0.421 kg/CM-d.[39] Assuming the crewmembers attempt to eat all of the consumable content within the food packages, about 0.076 kg/CM-d of hydrated food will adhere to the packaging when it is designated as trash. The corresponding oxygen consumption is 0.986 kg/CM-d, with carbon dioxide production of 1.182 kg/CM-d.[40] Supporting technology includes an undefined heating unit similar in size to a microwave oven.

3.2.8 IN-SITU RESOURCE UTILIZATION EXTERNAL INTERFACE

The CEV using the current technology life support system does not use in-situ resources.

3.2.9 POWER EXTERNAL INTERFACE

As envisioned by ESAS (2005), the primary CEV power system will use three buses operating at 28 Volts direct current. Two 17.9 m² (193 ft²) triple-junction, gallium-arsenic solar photovoltaic arrays deployed from the base of the Service Module, after assumed efficiencies and losses, each provide 4.5 kW_e of power generation at end-of-life. For operations when the solar arrays are not available, the CEV has redundant, rechargeable, lithium-ion batteries sized to provide 13.5 kW_eh of electrical energy from storage.

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[39] This value does not include secondary structure, such as racks. Rather, this value describes lockers.

[40] For a metabolic intake of 7.95 MJ/CM-d, Levri (2003) estimates 0.771 kg/CM-d of food mass overall, as-shipped, with 0.326 kg/CM-d of moisture and 0.445 kg/CM-d of dry food. To contain this food, packing adds 0.177 kg/CM-d and the locker adds another 0.233 kg/CM-d. 0.042 kg/CM-d of rehydrated food adheres to the packaging and is wasted. The corresponding oxygen consumption is 0.545 kg/CM-d, with carbon dioxide production of 0.652 kg/CM-d.

Based on ESAS (2005), the corresponding infrastructure penalties are 136.0 kg/kW_e [41] and 15.6 $kg/kW_e h$. [42]

3.2.10 RADIATION PROTECTION EXTERNAL INTERFACE

The CEV life support system architecture using current technologies has no interchange with the Radiation Protection External Interface. Rather, any radiation protection is provided by dedicated mass, such as polyethylene, integrated into the vehicle structure, and undedicated mass associated with vehicle hardware arranged about the periphery of the crew cabin.

According to ESAS (2005), the CEV has no dedicated mass for radiation protection. Rather, the mass associated with the structure and other hardware is deemed sufficient protection for the anticipated mission duration and radiation environment.

3.2.11 THERMAL EXTERNAL INTERFACE

As envisioned by ESAS (2005), the CEV thermal control system uses many current approaches coupled with advanced materials to collect, transport, and reject thermal loads from the vehicle.

Thermal load collection is via either a cabin condensing heat exchanger (CHX) or cold plates (CPs) positioned in contact with warm equipment. The cabin condensing heat exchanger regulates the cabin atmospheric temperature and humidity, while coldplates transfer equipment thermal loads, via conductivity, into the thermal transport fluid. According to ESAS (2005), the cabin condensing heat exchanger is sized to collect 0.75 kW_{th} with a corresponding heat acquisition penalty of 49.3 kg/kW_{th}, while the coldplates throughout the CEV are sized to collect 5.5 kW_{th} with a corresponding heat acquisition penalty of 11.8 kg/kW_{th}.

The CEV has two identical, redundant thermal-transport loops. The thermal transport fluid is a homogeneous, single-phase, liquid mixture composed of 60% propylene glycol and 40% water. To allow complete redundancy, each thermal collection device is served by both of the thermal transport loops, and both thermal transport loops flow to all thermal rejection devices. Further, each loop has two identical pumps, a primary and a backup. Both thermal transport loops are capable of transporting the full nominal thermal load of 6.25 kW_{th}. Accounting for all masses and capabilities, the corresponding penalty for thermal transport is 25.9 kg/kW_{th}.

Thermal rejection from CEV, according to ESAS (2005), is via radiant exchange or phase-change of a consumable liquid. Radiant rejection is through four 7.0 m^2 radiator panels mounted equally around the periphery of the Service Module exterior. The radiator panels were sized assuming a working fluid inlet temperature of 308 K (95 °F) and an exit temperature of 275 K (36 °F), with no more than two panels in direct sunlight at anytime. Panels not facing the Sun were assumed to see a cold environment at 100 K (- 279 °F). [43] The rejection capacity of the radiators for sizing was 8.0 kW_{th}. The ESAS (2005) estimates assume the radiator surface properties were equivalent to 10-mil silver Teflon with a solar absorptivity of 0.094 and an infrared emissivity of 0.888 with a radiator panel mass per radiant area of 3.5 kg/m^2. For radiant rejection, then, the corresponding penalty is 12.3 kg/kW_{th}. For high heat load situations or following separation of the Service Module from the Command Module for re-entry, the CEV Command Module has a multi-fluid evaporator. In space and above 30.5 km (100,000 ft) within Earth's atmosphere, the evaporator uses water with a total mission rejection capacity of 37,800 kJ. [44] Below 30.5 km (100,000 ft) within Earth's atmosphere, the evaporator uses Freon R-134a with a total mission rejection

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41. This value includes penalties for both power generation via solar photovoltaic cells and the power management and distribution (PMAD). The PMAD accounts for almost 100 kg/kW_e by itself within CEV and is necessary for supplying power from any source.
42. The assumed sizing criteria are 6.0 kW_e for 2.25 hours to provide energy for the Command Module from service-module-separation until final-landing-on-Earth. Because the batteries are rechargeable, other battery usage throughout the mission is less demanding.
43. While the statements in these last two sentences are reasonable assumptions during translunar transfer, in either LEO or LLO, depending on the long-wave infrared emissions from the planetary body, more than one radiator panel may see Sun at a time and the actual thermal environment can be much warmer than the values assumed for sizing components within ESAS (2005). Thus, thermal external interface component sizing remains a topic of on-going analysis within NASA.
44. Within ESAS (2005), these consumables are sized with a 20% margin, so the total water loaded for evaporative cooling could reject up to 45,200 kJ based on a heat of vaporization of 2,260 kJ/kg.

capacity of 10,800 kJ. [45] The sum rejection capability from both the water and Freon R-134a is 48,600 kJ, or 13.50 $kW_{th}h$. Coupling the rejection capacities of both fluid allocations, the corresponding penalty for thermal rejection via evaporative cooling is 10.7 $kg/kW_{th}h$. The duration over which CEV will rely on evaporative cooling appears to be 2.25 hours based on sizing assumptions in ESAS (2005). On launch, the CEV relies on thermal capacity associated with heating pre-chilled working fluid from the radiators until radiant rejection becomes possible in low-Earth orbit, so no additional penalty is incurred for this initial mission phase. [46]

As structured, the thermal penalties above are additive, and the proper overall penalty depends upon how the specific thermal load is collected, transported, and then rejected. For most life support hardware, thermal loads are collected using coldplates and rejected using radiators while the CEV is in space, and then via the evaporative heat rejection device as the CEV Command Module lands on Earth. Thus, the overall penalty for thermal control is 50.0 kg/kW_{th} in space plus 10.7 $kg/kW_{th}h$ for 2.25 h for systems that remain active during landing.

3.2.12 VEHICLE STRUCTURE

Based upon ESAS (2005), the capsule primary structure mass is 1,882 kg, with thermal protection totaling 894 kg, and other capsule systems, including landing systems, totaling 1,159 kg. The overall pressurized volume is 29.4 m^3, which provides 12-15 m^3 of habitable volume for the crew. Thus, the vehicle structure infrastructure penalty is 133.8 kg/m^3 based upon pressurized volume.

3.2.13 LOCATION FACTORS

Based on ESAS (2005), the gear ratio [47] for payload aboard CEV Command Module is 9.1:1. For a payload that remains aboard the CEV Service Module, and therefore does not return to Earth with the crew, the gear ratio is 7.3:1. Compared to the nomenclature in BVAD (2004), a gear ratio is comparable to a location factor. These factors assume the payload remains aboard CEV and does not transfer to the surface with the crew. See Section 4.2.13 for the location factor associated with payloads that remain with the crew throughout the mission.

3.3 CONTINGENCY AND CONTINGENCY RESPONSE

While the functionality above outlines a single-string life support system using current technologies, an actual flight-rated life support system is robust, with inherent capability to handle contingencies. HRRSS (2005) identifies current requirements for a human-rated spacecraft. The comments below mention two related aspects of an actual human-rated life support system architecture design: contingencies and responding to contingencies.

3.3.1 CONTINGENCIES

HRRSS (2005) states, under paragraph 3.1.1, that "Space systems shall be designed so that no two failures result in crew or passenger fatality or permanent disability (Requirement 34419)." [48] This requirement applies at all levels of a human-rated vehicle. While actual hardware failure modes are often unknown, most hardware may fail. Thus, a life support system architecture should be designed such that no two failures lead to overall failure of the life support system in all flight modes when the crew is present. For the CEV, some flight regimes are highly dynamic and place significant restrictions on crew mobility, such as ascent and re-entry, so life support hardware must function without human intervention during those events.

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[45] Within ESAS (2005), these consumables are sized with a 20% margin, so the total R-134a loaded for evaporative cooling could reject up to 12,960 kJ based on a heat of vaporization of 216 kJ/kg.

[46] If necessary or in the event of an abort, the evaporative heat rejection device can provide sufficient cooling to reach a safe landing.

[47] "Gear ratios" provide a convenient measure of the cost of increasing vehicle inert mass to overall mission mass. For example, 1 kg added to a mission element increases initial architecture mass in LEO (IMLEO) by 1 kg × Gear Ratio for the corresponding element.

[48] Paragraph 3.1.2 allows specific exceptions to paragraph 3.1.1. See HRRSS (2005) for details.

Additionally, current requirements for CEV specify two schedule-related contingency situations. CEV0280H (Lembeck, 2005a) specifies that CEV shall provide life support commodities for the crew, mainly food and water, for up to 36 hours following return to the Earth's surface to support situations where a surface recovery team is not immediately available to care for the crew. CEV0085H (Lembeck, 2005a) stipulates that CEV shall provide an additional 48 hours, threshold, or 72 hours, objective, of mission support to allow the crew to remain in LEO while awaiting clearance to land at the primary landing location. Similar planning numbers currently support Space Transportation System Orbiter operations to allow the crew to postpone landing until favorable conditions arise at landing sites in the United States.

3.3.2 CONTINGENCY RESPONSE

For the CEV mission profile, aside from the contingency responses implied above, the current exploration architecture, according to CTS0405G (Lembeck, 2005a), allows a second set of vehicles to conduct contingency or rescue missions anywhere within the nominal mission architecture. However, CTS0405G and related requirements do not specify the timing of a contingency or rescue mission. Thus, for this LDRM, assume that the crew will wait not more than 14 days, threshold, or 10 days, objective, for another vehicle if a catastrophic event disables their current vehicle without completely destroying its ability to support the crew. During contingency situations certain nominal crew functions, such as full-body cleansing, may be curtailed or eliminated.

As a practical measure, ESAS (2005), within the mass estimates, includes one full-cabin repressurization for contingency situations. Because CEV will nominally operate at the lower cabin pressure after launch, the lower cabin pressure can be assumed for this calculation. [49] Finally, Constellation documents specify a second cabin repressurization that appears to account for gases lost due to normal leakage over the mission. [50]

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49 While the lower cabin pressure is appropriate for a Lunar Outpost mission, the higher cabin pressure would be appropriate as a basis for repressurization for a crew rotation mission aboard CEV to International Space Station.

50 Note: Total mission equivalent masses should ***not*** include both a second cabin repressurization, per Constellation documents, and make-up gases for leakage because both of these approaches are designed to account for gas losses due to leakage.

While a second cabin repressurization will surely allow restoration of the vehicle atmosphere just before the crew returns, supporting CEV0520G (Lembeck, 2005a), it is unlikely that the nominal dormancy state for CEV will include complete depressurization of the crew cabin by any means because full vacuum may have deleterious effects on any items remaining aboard CEV. For example, while critical systems should be operable following exposure to vacuum, by requirement and practicality, less critical functionality, such as foam integrity, may be reduced. Further, assuming that nominal cabin repressurization initiates only after the crew departs from the lunar surface may impede crew ingress especially if the departure schedule is abbreviated to accommodate an emergency. Thus, under the nominal mission profile it is desirable to keep the crew cabin pressurized to the minimum nominal atmospheric pressure even during dormancy.

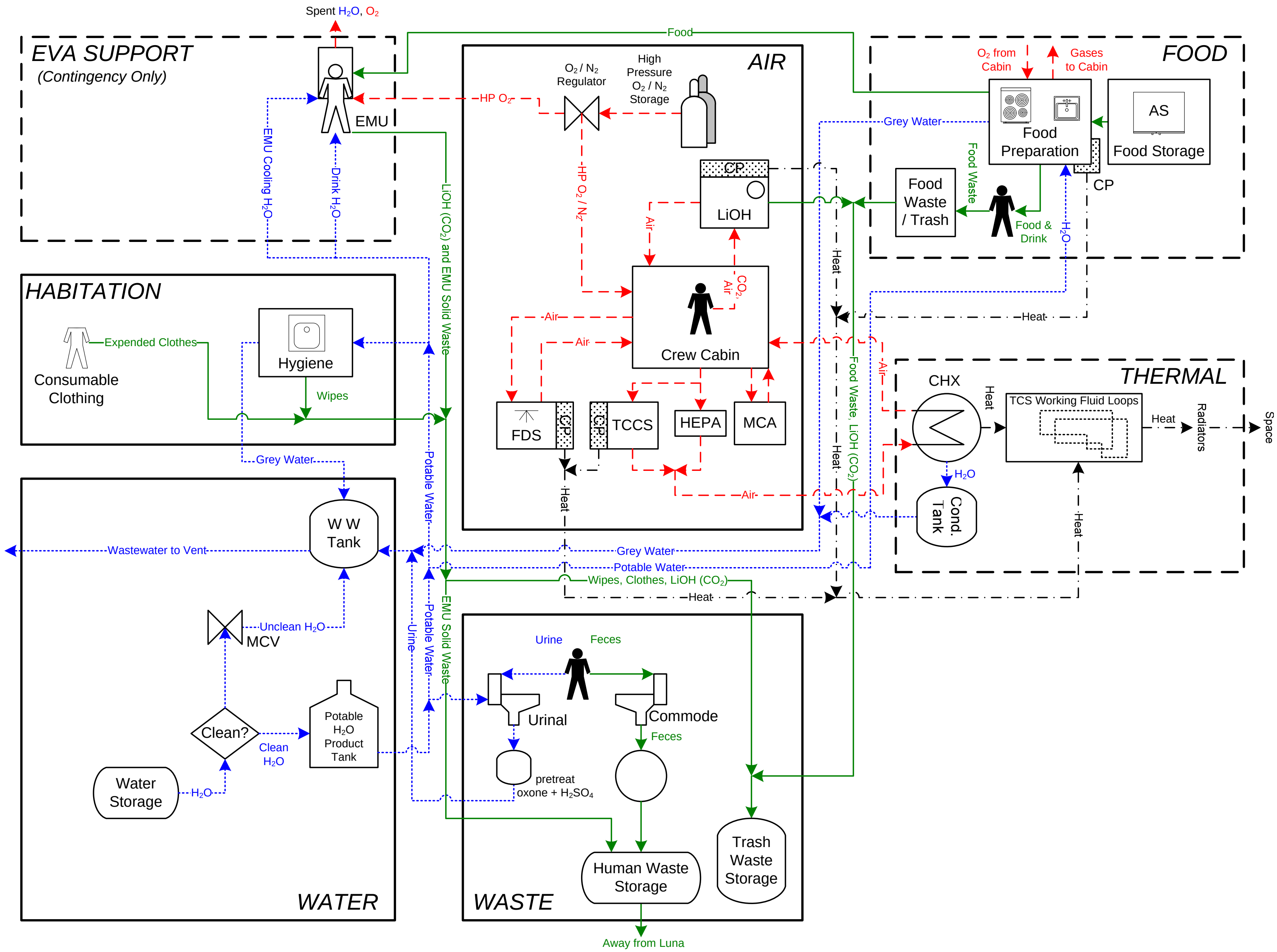

Figure 3.1 Crew Exploration Vehicle life support system using current technologies.

4 LUNAR SURFACE ACCESS MODULE FOR THE LUNAR REFERENCE MISSION

The emphasis in this section is on a second element of the crew transit infrastructure, the Lunar Surface Access Module (LSAM). The LSAM will transfer the crew from LLO to the surface of Luna, and from the surface of Luna to LLO. The LSAM will remain dormant on Luna with power supplied by a transmission line from the LO infrastructure while the crew conducts surface operations from the LO.

4.1 APPLICABLE REQUIREMENTS ASSOCIATED WITH THE LUNAR SURFACE ACCESS MODULE LIFE SUPPORT SYSTEM

The following criteria are discovered, as noted, in NASA documentation. Some values are derived from requirements while others are not. All, however, are mission-specific design decisions for this particular vehicle in this particular mission. Those subsystems that are not defined completely by mission-specific design decisions are specified more completely within the system based upon current operational technology in Section 4.2 below.

4.1.1 MISSION DURATION

The LSAM shall support a surface mission independently for up to 7 days (ESAS, 2005). [51] This duration applies for any surface site. To account for transit from and to a lunar orbit, the LSAM should be sized for one additional day of duration. [52] Additionally, the LSAM may be dormant on the surface of Luna for 42 days, threshold, and 360 days, objective, while the crew operates from the crew habitat of the LO. During this surface dormancy, the LSAM will receive sufficient power for all systems active during dormancy from an umbilical to the LO power system.

4.1.2 CAPACITY

For this mission, the crew size is 4 crewmembers (ESAS, 2005), for 5 days, inhabited, plus 42 days to 181 days, dormant, on Luna as described above.

4.1.3 AIR SUBSYSTEM

To support the overall mission, the LSAM cabin atmosphere will operate at two nominal values. The higher pressure setting, to be compatible with CEV during docking, is 70.3 kPa ± 1.4 kPa (10.2 psia ± 0.2 psia) with an oxygen (O_2) partial pressure of 18.6 kPa ± 0.028 kPa (26.5% ± 2.0%). The lower pressure setting, to be compatible with EVA surface operations, is 55.2 kPa ± 1.4 kPa (8.0 psia ± 0.2 psia) with an O_2 partial pressure of 17.7 kPa ± 0.028 kPa (32.0% ± 2.0%). See EAWG (2006). The diluent gas will be nitrogen (N_2). [53] Extrapolating from Constellation requirements for CEV, the maximum allowable partial pressure of carbon dioxide during nominal operations is 0.71 kPa (0.103 psia), and the minimum oxygen partial pressure is 16.0 kPa (2.32 psia).

Nominally, extrapolating from Constellation requirements for CEV, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s).

4.1.4 HABITATION SUBSYSTEM

Based on Constellation requirements for CEV, the crew shall be able to perform hand and body washing. The crew shall have clothing.

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[51] CTS0450G (Lembeck, 2005a) stipulates the LSAM shall support an independent surface mission for a duration of 4 days, threshold, and 7 days, objective. The threshold mission duration is roughly equivalent but slightly longer than the surface missions of the later Apollo flights, while the objective mission duration is twice that of the Apollo flights.

[52] The descent from lunar orbit to Luna and the ascent from Luna to lunar orbit are assumed to require no more than a half day each.

[53] Alternate diluent gases or gas mixtures could be used. Nitrogen is assumed in Robertson and Geffre (2004), although it is not, to date, required by either human physiology or NASA requirements.

4.1.5 WASTE SUBSYSTEM

The crew will generate wet and dry trash. Using CEV requirements from Constellation as a guide, the vehicle should provide odor control, stowage, and accessible trash collection for the Waste Subsystem. To support urination, the Waste Subsystem shall provide disposal of associated consumable wipe materials, collect 0.052 m³ of urine per flight [54], collect up to four urine discharges per hour, that may be up to 0.001 m³/discharge. To support fecal discharge, the Waste Subsystem shall provide disposal of associated consumable wipe materials, collect 0.150 kg/CM-d and 0.000150 m³/CM-d of fecal matter, collect up to 0.008 m³/CM/mission of diarrheal discharge, which may be discharged as 0.004 m³/CM-d of diarrhea or 0.002 m³/discharge event. Further, to meet anticipated future waste requirements derived from planetary protection requirements and treaties (UN, 1967), all human metabolic wastes must be contained for as long as they remain on Luna such that neither the crew nor the lunar surface are contaminated by human biological pathogens. To comply with these anticipated requirements derived from UN (1967) indefinitely, either the pathogens must be rendered incapable of further harmful action or the waste containing the pathogens must be removed from the lunar surface. [55]

4.1.6 WATER SUBSYSTEM

Using CEV requirements from Constellation as a guide, the crew in LSAM shall have 2.5 kg/CM-d of potable water, at a specified water quality during the nominal mission. For all purposes, cold water shall be 279.0 K ± 1.4 K (42.5 °F ± 2.5 °F), and hot water shall be 347.0 K ± 5.6 K (165 °F ± 10 °F).

Hygiene accommodations may also impact the Water Subsystem. The crew shall have 2.0 kg/CM-d for personal hygiene. [56] Water for body cleansing shall be 310.9 K ± 8.3 K (100 °F ± 15 °F). [57] While Constellation requirements assume the crew shall have clothing, there is no requirement to launder clothing.

4.1.7 EXTRAVEHICULAR ACTIVITY SUPPORT EXTERNAL INTERFACE

Extravehicular activity (EVA) provides the primary capability by which the crew transfers from the LSAM to the LO, enabling them to conduct an extended surface mission. EVA is also the primary means by which the crew will interact with the lunar surface environment.

4.1.7.1 AIRLOCK

Here it is assumed the LSAM has an airlock (A/L) capable of supporting two crewmembers in full extravehicular mobility units simultaneously (ESAS, 2005). A reasonable value for gas lost per cycle is 10% of the gas mass associated with free volume within the fully pressurized airlock. See BVAD (2004) for details. Assuming the EVA schedule listed in Section 4.1.7.3, with the entire crew conducting EVAs at the same time per ESAS (2005), each sortie from the LSAM requires multiple airlock depress and repress cycles.

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54 Constellation requirements stipulate collecting a volume of urine per crewmember in liters, $V_U = 3 + 2t$, where t is the mission duration in days. Assuming four crewmembers and a mission duration of up to 5 days for the LSAM when supporting a LO mission, the overall urine volume is 52 liters, or 0.052 m³.

55 Arguably human pathogens are unlikely to survive on Luna, even if released. However, as a precursor for martian missions, human biological markers must be sufficiently well contained so as to not interfere with science on Mars by being confused as possible markers for indigenous life.

56 This is an unofficial value based on discussions within NASA. The actual value here is unknown at this time.

57 While Constellation documents require water at 310.9 K ± 8.3 K for body cleansing, it does not prohibit combining other cold and hot potable water streams to generate the specified stream.

4.1.7.2 EXTRAVEHICULAR ACTIVITY PROCEDURES AND DEFINITIONS

A day of EVA is defined as 8 hours. [58] This duration includes airlock depress and repress. Each crewmember carries sufficient consumables upon leaving the airlock for the entire EVA; while "on-back weight" may limit carried consumable loads to less than what is necessary for a full day of EVA, it is assumed that sufficient consumables are available "close at hand" on the lunar surface for a full day of EVA and that the consumable stocks carried by the crew can be quickly and conveniently recharged without re-entering the LSAM or other surface vehicle during nominal mission operations. [59] During initiation and close-out activities, the entire crew conducts EVAs simultaneously.

4.1.7.3 FREQUENCY OF EXTRAVEHICULAR ACTIVITIES

For a mission simulating an initial martian exploration mission, EVA from the LSAM under a nominal mission profile is confined to post-descent operations prior to occupation of the LO crew habitat, noting that EVA operations just prior to ascent originate from the LO and only end in LSAM. Thus, from the perspective of the LSAM, EVA operations are invariant regardless of the duration of the surface mission from the LO. Upon arriving on Luna, all crewmembers conduct two days of EVA to prepare the LO for occupation. For sizing purposes, the crew initiates EVA from the LSAM during these operations, only ending the second day of EVA within the LO. Prior to ascent, the crew initiates a final EVA from the LO to prepare the exterior of the LO and the local site for dormancy. This final EVA prior to ascent will originate within the LO and end in the LSAM. For a crew of four, this protocol yields 12 CM-d_{EVA}, although the crew will use consumables from the LSAM equivalent to 8 CM-d_{EVA}. [60]

For missions where the incoming crew replaces a prior crew at a continuously-occupied site, the overall EVA schedule may be very similar, although the specific tasks may differ. After descending to the lunar surface, the arriving crew must still transfer its food and hardware for their upcoming mission either from the LSAM or a cargo pallet to appropriate storage in and about the LO. Prior to ascent, the departing crew must remove any samples for return to Earth plus any other items that are not to remain on Luna. Because planning for LO missions is very tentative at this time, these values are appropriate for analysis.

4.1.8 FOOD EXTERNAL INTERFACE

The Food Subsystem is not currently defined. However, extrapolating from CEV requirements from Constellation, the vehicle shall prevent cross-contamination between food preparation and personal hygiene areas, and between food preparation and body waste management areas. Food shall be rehydrated with hot or cold potable water. Finally, the vehicle should allow the crew to prepare a meal for all crewmembers within a single 30-minute period. Finally, due to the unique nature of LSAM compared to CEV, the vehicle shall prevent cross-contamination between the food preparation area and the EVA support area.

4.1.9 POWER EXTERNAL INTERFACE

The power utility architecture is not fully specified at this time. However, according to ESAS (2005), under nominal conditions, while LSAM actively houses the crew, the power utility will supply 3.5 kW_e. The unlimited peak power load is 5.0 kW_e. [61] While dormant on the surface, the LSAM will be supported with power from an external surface power source rather than an internal LSAM power source; the overall power usage while dormant is undefined, but 1.5 kW_e is assumed. While these values arise from a NASA study estimating LSAM power usage, they should not be viewed as limiting. Rather, these values underlie assumptions used to size the Power External Interface architecture described in Section 4.2.9.

[58] Or, one CM-d_{EVA} is equivalent to one crewmember conducting EVA for 8 hours.

[59] Specific operational details for EVAs are the responsibility of the appropriate authorities governing EVA. The values here only define the *expected* number of airlock cycles, based on analysis to date, so no additional EVA details should be inferred because operational EVA approaches remain an open issue at this time.

[60] Assuming a crew of six, this protocol yields 18 CM-d_{EVA}, although the crew will use consumables from the LSAM equivalent to 12 CM-d_{EVA}.

[61] A limited-duration peak load was not identified.

4.1.10 THERMAL EXTERNAL INTERFACE

The Thermal External Interface architecture is not fully defined to date. The thermal load is the sum of the hardware heat loads [62], plus the crew metabolic heat load, plus any environmental loads. [63] To account for the cabin heat load and waste heat generation associated with the power system, the Thermal External Interface is sized to reject 8.85 kW_{th} (ESAS, 2005). More specifically, 3.5 kW_{th} is collected by internal cold plates, 0.75 kW_{th} is collected by a cabin heat exchanger, and 4.6 kW_{th} is collected by external cold plates (ESAS, 2005). [64] As listed above, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s) per Constellation requirements.

4.2 LUNAR SURFACE ACCESS MODULE LIFE SUPPORT SYSTEM ARCHITECTURE USING CURRENT TECHNOLOGIES

An LSAM life support system architecture using current operational technologies is presented below to provide an initial overall design for analysts and system developers. The approach below might be viewed as a "baseline" for trade studies, but it certainly is *not* an optimized or officially recommended approach for a life support system within LSAM.

The cabin atmosphere is maintained with high-pressure gas stores and consumable carbon dioxide removal hardware. Clean water is provided from stores, while wastes are all stored. Food is pre-packaged, requiring only minor operations before consumption. The thermal management architecture relies on coldplates, heat exchangers, single-phase flow loops, and radiators. See Figure 4.1. Note that while Figure 4.1 presents pictorially a single-string life support system, this is merely for "artistic clarity" and is not meant to imply that LSAM will use a single-string life support system in practice. (Acronyms used in Figure 4.1 are listed in Section 8.)

4.2.1 AIR SUBSYSTEM

The air suite for the LSAM using current technology uses non-regenerable carbon dioxide (CO_2) removal equipment based on lithium hydroxide (LiOH). The trace contaminant control system (TCCS) for atmospheric gases uses activated carbon for non-combustible trace gas removal, and high efficiency particulate air (HEPA) filters for bacteria and particulate removal, neither of which are regenerated. Further, the TCCS also removes trace combustible gases from the crew cabin. Oxygen (O_2) and nitrogen (N_2) are supplied as pressurized gases from high-pressure stores. A major constituent analyzer (MCA) and a fire detection and suppression (FDS) system monitor for air contaminants and combustion products. Using CEV as an example, the cabin atmospheric leakage rate, aside from airlock losses, is no greater than 0.15 kg/d (ESAS, 2005).

4.2.2 HABITATION SUBSYSTEM

The LSAM life support architecture using current technologies assumes all clothing is brought pre-packaged from Earth at a rate of 0.46 kg/CM-d (ESAS, 2005) and used clothing is sent to the Waste Subsystem when it is no longer fit to wear. Disposable wipes at a rate of 0.15 kg/CM-d (ESAS, 2005) provide the crew with body cleansing and housekeeping support, although, unlike CEV, some potable water is available for body hygiene while the crew is on the surface of Luna. Additionally, ESAS (2005) provides 5 kg/CM for recreational supplies and 2.3 kg/CM for sleep accommodations.

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[62] When unavailable, as a first approximation, the hardware heat load discharged for the thermal external interface to remove may be taken as equal to its input power. Note that because other heat rejection routes and chemical reaction kinetics, this assumption may be conservative.

[63] Environmental loads are unique to each vehicle; net environmental loads are normally small or zero when considered over the entire vehicle. Until a value is defined for LSAM, assume net environmental loads are zero.

[64] There is one external coldplate for each of three fuel cells. The power architecture is two-fault tolerant, providing full power after up to two failures. Thus, even though each fuel cell must have its own coldplate, only one fuel will be operational at a time, so the total heat load collected, for purposes of sizing the thermal external interface, is equivalent to the load from only one fuel cell.

4.2.3 WASTE SUBSYSTEM

The Waste Subsystem provides only rudimentary collection and storage of waste products. The waste suite includes a toilet, pretreatment to stabilize urine, and separate storage volumes for human liquid and solid metabolic wastes and trash. Human liquid and solid metabolic wastes will return with the crew to comply with international treaty (UN, 1967).

4.2.4 WATER SUBSYSTEM

The LSAM Water Subsystem using current technologies provides water from stores. When the LSAM operates using its own independent energy system, the stores are filled with process water that is a by-product of generating power via fuel cells. A process control water quality monitor samples dispensed water to assure overall water safety.

4.2.5 CREW EXTERNAL INTERFACE

See Section 2.4.3 for a description of crewmembers.

4.2.6 EXTRAVEHICULAR ACTIVITY SUPPORT EXTERNAL INTERFACE

According to ESAS (2005), the free airlock (A/L) internal volume within the LSAM is 5.1 m^3. BVAD (2004) provides estimates based on current technology, such as EVA life-support commodity usage. For the LSAM life support architecture using current technology, lithium hydroxide (LiOH) cartridges remove carbon dioxide from the extravehicular mobility unit (EMU) atmosphere. The cartridges themselves are a consumable normally attributable to the extravehicular activities system and not to the life support system.

4.2.7 FOOD EXTERNAL INTERFACE

Food is provided as individual entrées in the LSAM architecture using current technologies. This diet relies on a variety of ambient-temperature storage (AS) foods. For the design case, this approach supplies 14.40 MJ/CM-d of metabolic energy for intravehicular activities. Employing Levri (2003) and assuming the Shuttle Training Menu as the applicable basis, the design-case metabolic energy corresponds to 1.397 kg/CM-d of food overall. The food mass, as-shipped, is 0.592 kg/CM-d moisture, or 42%, and 0.805 kg/CM-d dry food. An additional 0.321 kg/CM-d of disposable packaging directly protects the food, and specialized food-storage structure, or locker, adds an additional 0.421 kg/CM-d. [65] Assuming the crewmembers attempt to eat all of the consumable content within the food packages, about 0.076 kg/CM-d of hydrated food will adhere to the packaging when it is designated as trash. The corresponding oxygen consumption is 0.986 kg/CM-d, with carbon dioxide production of 1.182 kg/CM-d. [66] Supporting technology includes an undefined heating unit similar in size to a microwave oven. These values are identical to those supplied while the crew is aboard CEV. See Section 3.2.7.

[65] This value does not include secondary structure, such as racks. Rather, this value describes lockers.

[66] For a metabolic intake of 7.95 MJ/CM-d, Levri (2003) estimates 0.771 kg/CM-d of food mass overall, as-shipped, with 0.326 kg/CM-d of moisture and 0.445 kg/CM-d of dry food. To contain this food, packing adds 0.177 kg/CM-d and the locker adds another 0.233 kg/CM-d. 0.042 kg/CM-d of rehydrated food adheres to the packaging and is wasted. The corresponding oxygen consumption is 0.545 kg/CM-d, with carbon dioxide production of 0.652 kg/CM-d.

For days with extravehicular activities, the design case requires additional food (Lane, *et al.*, 1996). Specifically, this approach supplies 16.49 MJ/CM-d of metabolic energy to a 95th percentile male for both intravehicular and extravehicular activities. Employing Levri (2003) and assuming the Shuttle Training Menu as the applicable basis, the design-case metabolic energy corresponds to 1.600 kg/CM-d of food overall. The food mass, as-shipped, is 0.678 kg/CM-d moisture, or 42%, and 0.922 kg/CM-d dry food. An additional 0.368 kg/CM-d of disposable packaging directly protects the food, and specialized food-storage structure, or locker, adds an additional 0.483 kg/CM-d. Assuming the crewmembers attempt to eat all of the consumable content within the food packages, about 0.088 kg/CM-d of hydrated food will adhere to the packaging when it is designated as trash. The corresponding oxygen consumption is 1.130 kg/CM-d, with carbon dioxide production of 1.353 kg/CM-d. [67]

4.2.8 In-Situ Resource Utilization External Interface

The LSAM life support system using current technologies does not use in-situ resources.

4.2.9 Power External Interface

According to ESAS (2005), the primary LSAM power system will use three buses operating at 28 Volts direct current. Three proton exchange membrane (PEM) fuel cells, each sized to deliver up to 5.0 kWe, provide two-fault tolerance for power generation and are located on the LSAM Descent Stage. The average power consumption is 2.41 kW_e for up to 18.7 days (ESAS, 2005). [68] The fuel cell reactants are sized to provide 1,080 kW_eh. After lift-off from the lunar surface, four rechargeable lithium-ion batteries supply electricity for the Ascent Stage through docking with and transfer of the crew to the CEV. The batteries will also provide sufficient electricity for guidance during the Ascent Stage's disposal maneuver. These batteries store 16.0 kW_eh of electric energy (ESAS, 2005). Based on ESAS (2005), the corresponding infrastructure penalties are 166.2 kg/kW_e [69] plus 0.528 kW_eh to account for fuel cell reactants. During ascent, the energy cost is 12.3 kg/kW_eh. While the LSAM is dormant on the lunar surface, the appropriate values for power generation are, to a first approximation, those associated with the LO power facility in Section 5.2.9.

4.2.10 Radiation Protection External Interface

The LSAM life support system architecture using current technologies has no interchange with the Radiation Protection External Interface. Rather, any radiation protection is provided by dedicated mass, such as polyethylene, integrated into the vehicle structure, and undedicated mass associated with vehicle hardware arranged about the periphery of the crew cabin.

According to ESAS (2005), the LSAM has no dedicated mass for radiation protection. Rather, the mass associated with the structure and other hardware is deemed sufficient protection for the anticipated mission duration and radiation environment.

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67 For a metabolic intake of 10.04 MJ/CM-d, which corresponds to a 5th percentile female for intravehicular and extravehicular activities, Levri (2003) estimates 0.974 kg/CM-d of food mass overall, as-shipped, with 0.412 kg/CM-d of moisture and 0.562 kg/CM-d of dry food. To contain this food, packing adds 0.224 kg/CM-d and the locker adds another 0.294 kg/CM-d. 0.053 kg/CM-d of rehydrated food adheres to the packaging and is wasted. The corresponding oxygen consumption is 0.688 kg/CM-d, with carbon dioxide production of 0.824 kg/CM-d.

68 The LSAM mission life includes several days in low-Earth orbit docked with the EDS awaiting rendezvous with CEV. Thus, 18.7 days should not be construed to be equivalent to the duration that the crew occupies LSAM.

69 This value includes penalties for the power generation hardware associated with the fuel cells plus the power management and distribution (PMAD).

4.2.11 THERMAL EXTERNAL INTERFACE

From ESAS (2005), the LSAM thermal control system uses current approaches coupled with advanced materials to collect, transport, and reject thermal loads from the vehicle.

Thermal load collection is via either a cabin condensing heat exchanger (CHX) or cold plates (CPs) positioned in contact with warm equipment. The cabin condensing heat exchanger regulates the cabin atmospheric temperature and humidity, while coldplates transfer equipment thermal loads, via conductivity, into the thermal transport fluid. According to ESAS (2005), the cabin condensing heat exchanger is sized to collect 0.75 kW_{th} with a corresponding heat acquisition penalty of 49.3 kg/kW_{th}, while the coldplates throughout the LSAM are sized to collect 5.5 kW_{th} with a corresponding heat acquisition penalty of 8.8 kg/kW_{th}.

The LSAM has two identical, redundant thermal-transport loops. The thermal transport fluid is a homogeneous, single-phase, liquid mixture composed of 60% propylene glycol and 40% water. To allow complete redundancy, each thermal collection device is served by both of the thermal transport loops, and both thermal transport loops flow to all thermal rejection devices. Further, each loop has two identical pumps, a primary and a backup. Both thermal transport loops are capable of transporting the full nominal thermal load of 8.85 kW_{th}. Accounting for all masses and capabilities, the corresponding penalty for thermal transport is 15.8 kg/kW_{th}.

Thermal rejection from LSAM is via radiant exchange or phase-change of a consumable liquid. Radiant rejection is through four 4.8 m^2 radiator panels mounted equally around the periphery of the Descent Stage exterior. For radiant rejection, then, the corresponding penalty is 8.5 kg/kW_{th}. For high heat load situations or following separation of the Ascent Stage from the Descent Stage for return to LLO, the LSAM Ascent Stage has a water evaporator with consumable water to support a total mission rejection capacity of 41,600 kJ. [70] The nominal rejection capability is 11.6 $kW_{th}h$ with a corresponding penalty for thermal rejection via evaporative cooling of 6.7 $kg/kW_{th}h$.

Again, the thermal penalties above are additive, and the proper overall penalty depends upon how the specific thermal load is collected, transported, and then rejected. For most life support hardware, thermal loads are collected using coldplates and rejected using radiators before the LSAM Ascent Stage separates from the Descent Stage, and then via the evaporative heat rejection device after the LSAM Ascent Stage separates from the Descent Stage. Thus, the overall penalty for thermal control is 33.1 kg/kW_{th} before separation plus 6.7 $kg/kW_{th}h$ for systems that remain active after separation.

4.2.12 VEHICLE STRUCTURE

Based upon ESAS (2005), the LSAM Ascent Stage primary structure mass is 1,024 kg, with distributed thermal protection totaling 113 kg. Hatches, windows and like components add another 382 kg. The overall pressurized volume is 24.6 m^3, divided as 16.7 m^3 for an "Ascent/Descent/Surface Living Module" and 7.9 m^3 for a two-person Airlock. The corresponding habitable volume is 8.7 m^3 in the "Ascent/Descent/Surface Living Module" and 5.1 m^3 in the airlock. Thus, the LSAM Ascent Stage vehicle structure has a volume-mass penalty of 61.7 kg/m^3 based upon pressurized volume.

4.2.13 LOCATION FACTORS

Based on ESAS (2005), the gear ratio for payload aboard LSAM Ascent Stage is 13.8:1. For a payload that remains aboard the LSAM Descent Stage, and therefore does not leave Luna with the crew, the gear ratio is only 7.2:1. These factors assume the payload remains aboard LSAM and does not transfer to CEV with the crew. Finally, for a payload that travels with the crew throughout the mission, traveling in the CEV, descending to Luna on LSAM, and returning to Earth with the crew on CEV, the gear ratio is 18.7:1 (Geffre, 2006). See Section 3.2.13 for the location factors associated with payloads that remain aboard CEV throughout the mission.

[70] Within ESAS (2005), these consumables are sized with a 20% margin, so the total water loaded for evaporative cooling could reject up to 52,000 kJ based on a heat of vaporization of 2,260 kJ/kg.

4.3 CONTINGENCY AND CONTINGENCY RESPONSE

While the functionality above outlines a single-string life support system using current technologies, an actual flight-rated life support system is robust, with inherent capability to handle contingencies. HRRSS (2005) identifies current requirements for a human-rated spacecraft. The comments below mention two related aspects of an actual human-rated life support system architecture design: contingencies and responding to contingencies.

4.3.1 CONTINGENCIES

HRRSS (2005) states, under paragraph 3.1.1, that "Space systems shall be designed so that no two failures result in crew or passenger fatality or permanent disability (Requirement 34419)." [71] This requirement applies at all levels of a human-rated vehicle. While actual hardware failure modes are often unknown, most hardware may fail. Thus, a life support system architecture should be designed such that no two failures lead to overall failure of the life support system in all flight modes when the crew is present. For the LSAM, some flight regimes are highly dynamic, such as lunar descent and ascent, so life support hardware must function without human intervention during those events. Unlike CEV, current requirements for LSAM have not specified any additional contingency situations yet.

4.3.2 CONTINGENCY RESPONSE

According to CTS0405G (Lembeck, 2005a), a second set of vehicles may conduct contingency or rescue missions anywhere within the nominal mission architecture. However, CTS0405G and related requirements do not specify the timing of a contingency or rescue mission. Thus, for this LDRM, assume that the crew will wait not more than 14 days, threshold, or 10 days, objective, for another vehicle if a catastrophic event disables their current vehicle without completely destroying its ability to support the crew. During contingency situations certain nominal crew functions, such as full-body cleansing or nominal EVA operations, may be curtailed or eliminated.

As a practical measure, ESAS (2005), within the mass estimates, includes one full-cabin repressurization for contingency situations for CEV. In like manner, one full-cabin repressurization should be included for LSAM. Because LSAM must operate at the higher cabin pressure to dock with CEV for the trip back to Earth, the higher cabin pressure should form the basis for this calculation. Finally, in some studies, NASA analysts carry a second cabin repressurization to account for gases lost due to normal leakage over the mission. [72]

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[71] Paragraph 3.1.2 allows specific exceptions to paragraph 3.1.1. See HRRSS (2005) for details.

[72] Note: Total mission equivalent masses should ***not*** include both a second cabin repressurization and make-up gases for leakage because both of these approaches are designed to account for gas losses due to leakage.

While a second cabin repressurization will surely allow restoration of the vehicle atmosphere just before the crew returns, supporting requirements similar to CEV0520G (Lembeck, 2005a) for CEV, it is unlikely that the nominal dormancy state for LSAM will include complete depressurization of the crew cabin, other than the airlock, by any means because full vacuum may have deleterious effects on any items remaining aboard LSAM. For example, while critical systems should be operable following exposure to vacuum, by requirement and practicality, less critical functionality, such as foam integrity, may be reduced. Further, assuming that nominal cabin repressurization initiates only after the crew returns to LSAM to depart from the lunar surface may impede crew ingress especially if the departure schedule is abbreviated to accommodate an emergency. Thus, under the nominal mission profile it is desirable to keep the crew cabin pressurized to the minimum nominal atmospheric pressure even during dormancy.

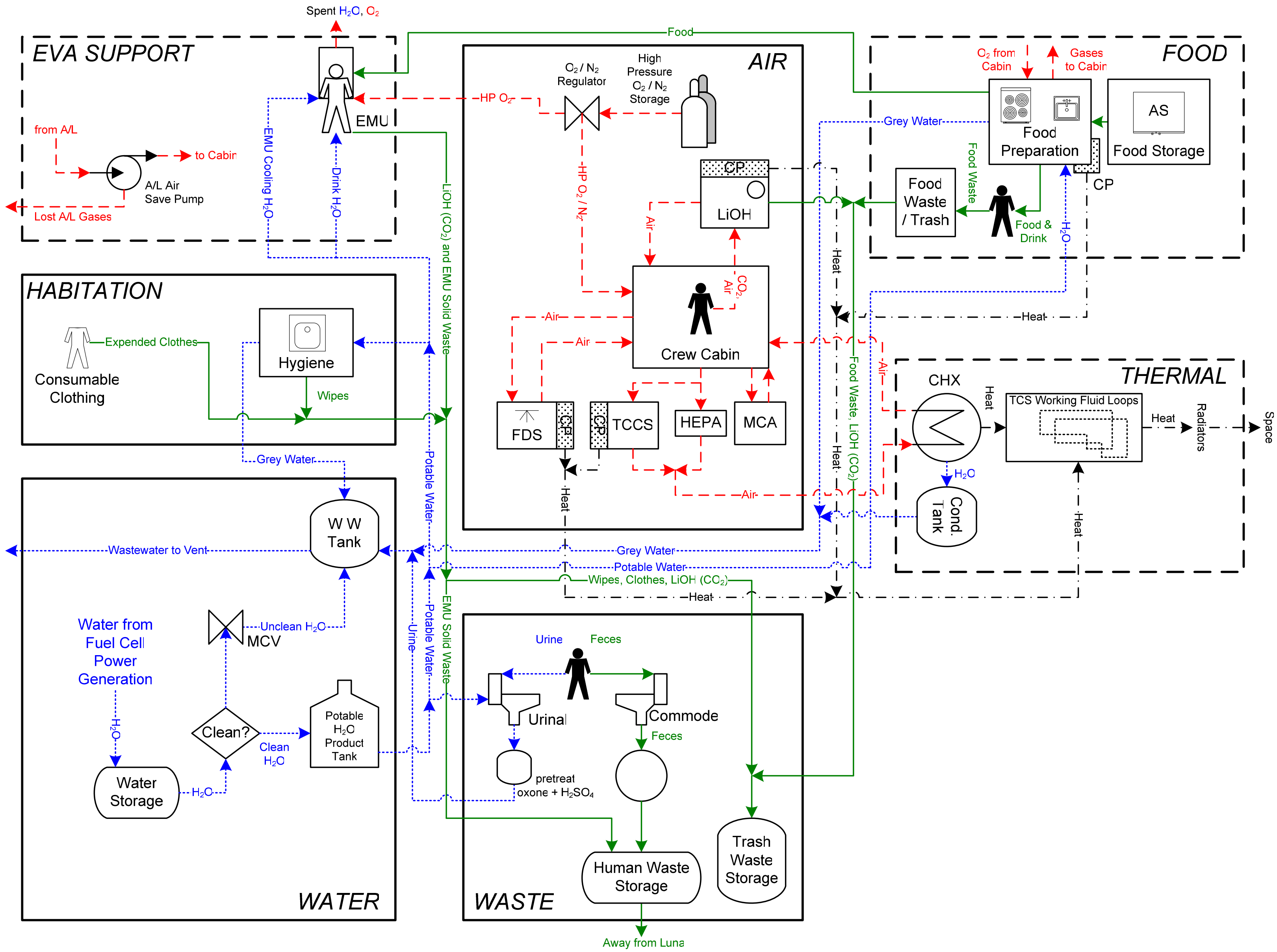

Figure 4.1 Lunar Surface Access Module life support system using current technologies.

5 LUNAR OUTPOST FOR THE LUNAR REFERENCE MISSION

The emphasis in this section is on a long-duration surface habitat for the crew, the Lunar Outpost, (LO). [73] While the elements of the LO will arrive autonomously at a pre-selected site, its presence allows the crew to conduct extended-duration exploration within its vicinity.

5.1 APPLICABLE REQUIREMENTS ASSOCIATED WITH THE LUNAR OUTPOST LIFE SUPPORT SYSTEM

The following criteria are discovered, as noted, in NASA documentation. Some values are derived from requirements while others are not. All, however, are mission-specific design decisions for this particular vehicle in this particular mission. Those subsystems that are not defined completely by mission-specific design decisions are specified more completely within the system based upon current operational technology in Section 5.2 below.

5.1.1 MISSION DURATION

The LO shall support a threshold surface mission duration of 42 days and an objective surface mission duration for an individual crew of no more than 181 days (ESAS, 2005). [74] These durations apply equally for polar or equatorial sites. Depending upon the overall mission scenario, the LO facility life may be much longer than the duration for a single crew's mission. See Section 2.3 for detailed descriptions of the projected life for various LO facilities.

5.1.2 CAPACITY

For this mission, the crew size is 4 crewmembers (ESAS, 2005), for 42 days to 181 days inhabited per crew as described above. During the crew rotation, LO may be occupied by up to two crews, or 8 crewmembers, for up to 8 days out of every 181 day-mission. As discussed in Section 2.3, the overall facility life may be longer.

5.1.3 AIR SUBSYSTEM

The overall pressure within LO, to be compatible with EVA surface operations, is 55.2 kPa ± 1.4 kPa (8.0 psia ± 0.2 psia) with an O_2 partial pressure of 17.7 kPa ± 0.028 kPa (32.0% ± 2.0%). See EAWG (2006). The diluent gas will be nitrogen (N_2). [75] Extrapolating from requirements for CEV from Constellation, the maximum allowable partial pressure of carbon dioxide during nominal operations is 0.71 kPa (0.103 psia), and the minimum oxygen partial pressure is 16.0 kPa (2.32 psia).

Nominally, extrapolating from Constellation requirements for CEV, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s).

5.1.4 HABITATION SUBSYSTEM

Based on Constellation requirements for CEV, the crew shall be able to perform hand and body washing. The crew shall have clothing.

5.1.5 WASTE SUBSYSTEM

The crew will generate wet and dry trash. Using CEV requirements from Constellation as a guide, the vehicle should provide odor control, stowage, and accessible trash collection for the Waste Subsystem. To support urination, the Waste Subsystem shall provide disposal of associated consumable wipe materials,

[73] While the discussion here will focus primarily upon the crew habitat for the Lunar Outpost, the Lunar Outpost has several elements in addition to a crew habitat as implied by nomenclature seen to date.

[74] Total mission durations are discussed in more detail in Section 2.3. Based upon that discussion, the true objective mission duration will vary depending on the overall goals of each specific LO.

[75] Alternate diluent gases or gas mixtures could be used. Nitrogen is assumed in Robertson and Geffre (2004), although it is not, to date, required by either human physiology or NASA requirements.

collect 1.46 m^3 of urine per crew [76], collect up to four urine discharges per hour, that may be up to 0.001 m^3/discharge. To support fecal discharge, the Waste Subsystem shall provide disposal of associated consumable wipe materials, collect 0.150 kg/CM-d and 0.000150 m^3/CM-d of fecal matter, collect up to 0.008 m^3/CM/mission of diarrheal discharge, which may be discharged as 0.004 m^3/CM-d of diarrhea or 0.002 m^3/discharge event. [77] Further, to meet anticipated future waste requirements derived from planetary protection requirements and treaties (UN, 1967), all human metabolic wastes must be contained for as long as they remain on Luna such that neither the crew nor the lunar surface are contaminated by human biological pathogens. To comply with these anticipated requirements derived from UN (1967) indefinitely, either the pathogens must be rendered incapable of further harmful action or the waste containing the pathogens must be removed from the lunar surface. [78]

5.1.6 WATER SUBSYSTEM

Using CEV requirements for Constellation as a guide, the crew in LO shall have 2.5 kg/CM-d of potable water, at a specified water quality during the nominal mission. For all purposes, cold water shall be 279.0 K ± 1.4 K (42.5 °F ± 2.5 °F), and hot water shall be 347.0 K ± 5.6 K (165 °F ± 10 °F).

Hygiene accommodations may also impact the Water Subsystem. The crew shall have 5.45 kg/CM-d for personal hygiene (7.2.5.3.6, MSIS, 1995). Water for body cleansing shall be 310.9 K ± 8.3 K (100 °F ± 15 °F) from Constellation requirements. [79] While Constellation requirements assume the crew shall have clothing, there is no requirement to launder clothing.

5.1.7 EXTRAVEHICULAR ACTIVITY SUPPORT EXTERNAL INTERFACE

Extravehicular activity (EVA) provides the primary capability for the crew to explore the region surrounding the LO and complete local extraterrestrial science.

5.1.7.1 AIRLOCK

The LO has an airlock (A/L) capable of supporting two crewmembers in full extravehicular mobility units simultaneously. A reasonable value for gas lost per cycle is 10% of the gas mass associated with free volume within the fully pressurized airlock. See BVAD (2004) and Section 5.2.6 below for details.

5.1.7.2 EXTRAVEHICULAR ACTIVITY PROCEDURES AND DEFINITIONS

A day of EVA is defined as 8 hours. [80] This duration includes airlock depress and repress. Each crewmember carries sufficient consumables for the entire EVA. [81] For exploration, an EVA sortie consists of two crewmembers. During initiation or arrival and just before departure, the entire crew conducts EVAs simultaneously.

5.1.7.3 FREQUENCY OF EXTRAVEHICULAR ACTIVITIES

During an initial 42-day mission to the LO, the crew conducts 14 days of EVA. Specifically, after arrival, all crewmembers spend two days in EVA to prepare the LO crew habitat for occupation by activating the LO crew habitat and transferring consumables and experimental hardware from cargo to

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76 Constellation requirements stipulate collecting a volume of urine per crewmember in liters, $V_U = 3 + 2t$, where t is the mission duration in days. Assuming four crewmembers and a mission duration of up to 181 days for an LO mission, the overall urine volume is 1,460 liters, or 1.46 m^3.

77 Constellation requirements support crew motion sickness associated with acclimating to a weightless environment. It is highly likely that most crewmembers will be completely acclimated by the time they reach the LO. However, for longer-duration missions there is a risk of a crewmember becoming ill for other reasons, so these requirements, derived from CEV to treat motion sickness, may not be sufficient to support the crew for other illnesses in LO.

78 Arguably human pathogens are unlikely to survive on Luna, even if released. However, as a precursor for martian missions, human biological markers must be sufficiently well contained so as to not interfere with science on Mars by being confused as possible markers for indigenous life.

79 While Constellation documents require water at 310.9 K ± 8.3 K for body cleansing, it does not prohibit combining other cold and hot potable water streams to generate the specified stream.

80 Or, one CM-d_{EVA} is equivalent to one crewmember conducting EVA for 8 hours.

81 Specific operational details for EVAs are the responsibility of the appropriate authorities governing EVA. The values here only define the *expected* number of airlock cycles, based on analysis to date, so no additional EVA details should be inferred because operational EVA approaches remain an open issue at this time.

storage in and around the LO. In the following weeks, the crew conducts 11 days of EVA sorties for exploration with two crewmembers per sortie. On average, this corresponds to two days of EVA per week during the exploration phase. Finally, to prepare for departure, the entire crew conducts an EVA the last day. For a crew of four, this protocol yields 34 $CM\text{-}d_{EVA}$ for the entire mission with 22 $CM\text{-}d_{EVA}$ for exploration. Because all EVAs to prepare the LO for crew arrival initiate in the LSAM, per Section 4.1.7.3, the crew uses consumables from the LO equivalent to 26 $CM\text{-}d_{EVA}$ for the entire mission. [82]

During an 181-day mission from the LO, the crew conducts 104 days of EVA. At LO activation, the entire crew spends two days in EVA to prepare the LO for occupation. During the exploration phase, the crew conducts an additional 101 days of EVA sorties with two crewmembers per sortie. On average, this schedule corresponds to four days of EVA per week during the exploration phase. In preparation for departure, the entire crew conducts an EVA on the last day. This assumed protocol is more aggressive than for a 42-day mission because the 181-day expeditions represent more mature missions. This further assumes that EVA technologies are compatible with this schedule. For a crew of four, this protocol yields 214 $CM\text{-}d_{EVA}$ for the entire mission and 202 $CM\text{-}d_{EVA}$ for exploration with an overall load on the LO equivalent to 206 $CM\text{-}d_{EVA}$. [83]

5.1.8 *FOOD EXTERNAL INTERFACE*

The Food Subsystem is not currently defined. However, extrapolating from CEV Constellation requirements, the vehicle shall prevent cross-contamination between food preparation and personal hygiene areas, and between food preparation and body waste management areas. Food shall be rehydrated with hot or cold potable water. Finally, the vehicle should allow the crew to prepare a meal for all crewmembers within a single 30-minute period. Finally, due to the unique nature of LO compared to CEV, the vehicle shall prevent cross-contamination between the food preparation area and the EVA support area.

5.1.9 *POWER EXTERNAL INTERFACE*

The power utility will supply 25 kW_e to the LO while it actively houses the crew, per ESAS (2005). While the LO is dormant, assume the power utility will supply up to 3 kW_e. [84] The power utility architecture is not specified at this time. The values here arise from a NASA study estimating LO power usage. However, they should not be viewed as limiting. Rather, these values underlie assumptions used to size the Power External Interface architecture described in Section 5.2.9.

5.1.10 *THERMAL EXTERNAL INTERFACE*

The Thermal External Interface architecture is not defined to date. The thermal load is the sum of the hardware heat loads [85], plus the crew metabolic heat load, plus any environmental loads. [86] The supplied power, Section 5.1.9, is indicative of the overall hardware heat load, while the metabolic energy intake by the crew, Section 2.4.3, is indicative of the crew metabolic heat load, assuming the crewmembers themselves are neither gaining nor losing body-mass. For the LO, the power generation hardware is most likely detached from the crew habitat, so thermal loads associated with power generation are rejected independently of waste heat from the crew habitat. As listed above in Constellation requirements for CEV, the cabin atmospheric temperature shall be from 291 K (65 °F) to 300 K (80 °F), with a dew point of 278 K (40 °F) to 289 K (60 °F), and a ventilation velocity of 0.079 m/s (0.26 ft/s) to 0.20 m/s (0.65 ft/s).

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82 For a crew of six, this protocol yields 40 $CM\text{-}d_{EVA}$ over the entire mission with 22 $CM\text{-}d_{EVA}$ for exploration. For this approach, the LO must supply consumables equivalent to 28 $CM\text{-}d_{EVA}$.

83 For a crew of six, this protocol yields 220 $CM\text{-}d_{EVA}$ for the entire mission and 202 $CM\text{-}d_{EVA}$ for exploration with an overall load on the LO equivalent to 208 $CM\text{-}d_{EVA}$.

84 While the mission architecture here does not specify a dormant period for LO after initial crew arrival, this value is provided for completeness.

85 When actual thermal loads are unavailable, as a first approximation, the hardware heat load discharged for the thermal management subsystem to remove may be taken as equal to its input power. Note that because other heat rejection routes and chemical reaction kinetics, this assumption may be conservative.

86 Environmental loads are unique to each vehicle; net environmental loads are normally small or zero when considered over the entire vehicle. Until a value is defined for LO, assume net environmental loads are zero.

5.2 LUNAR OUTPOST LIFE SUPPORT SYSTEM ARCHITECTURE USING CURRENT TECHNOLOGIES

A baseline LO life support system architecture, using current operational technologies, is presented below to provide an initial overall design for analysts and system developers. The approach below might be viewed as a "baseline" for trade studies, but it certainly is *not* an optimized or officially recommended approach for a life support system within LO.

The cabin atmosphere is maintained with high-pressure gas stores and regenerable carbon dioxide removal hardware. Clean water is provided using hardware developed for ISS, while wastes are all stored. Food is pre-packaged, requiring only minor operations before consumption. The thermal management architecture relies on coldplates, heat exchangers, single-phase fluid loops, and radiators. Oxygen, water, and food are supplied to support extravehicular activities. See Figure 5.1. Note that while Figure 5.1 presents pictorially a single-string life support system, this is merely for "artistic clarity" and is not meant to imply that LO will use a single-string life support system in practice. (Acronyms used in Figure 5.1 are listed in Section 8.)

5.2.1 AIR SUBSYSTEM

The air suite for the LO with current or near-term technologies uses regenerable carbon dioxide (CO_2) removal equipment based on molecular sieve technology, which is a four-bed molecular sieve (4BMS). Absorbed carbon dioxide is dissociated from the absorbing media and exhausted from the vehicle without recovering any commodities. The trace contaminant control system (TCCS) for atmospheric gases uses activated carbon for non-combustible trace gas removal, and high efficiency particulate air (HEPA) filters for bacteria and particulate removal, neither of which are regenerated. Further, the TCCS also removes trace combustible gases from the crew cabin. Oxygen (O_2) and nitrogen (N_2) are supplied as pressurized gases from high-pressure stores. A major constituent analyzer (MCA) and a fire detection and suppression (FDS) system monitor for air contaminants and combustion products. Using CEV as an example, the cabin atmospheric leakage rate, aside from airlock losses, is no greater than 0.15 kg/d (ESAS, 2005). [87]

5.2.2 HABITATION SUBSYSTEM

Based upon CEV and LSAM estimates in ESAS (2005), the LO life support architecture using current technologies assumes all clothing is brought pre-packaged from Earth at a rate of 0.46 kg/CM-d and used clothing is sent to the Waste Subsystem when it is no longer fit to wear. Disposable wipes at a rate of 0.15 kg/CM-d (ESAS, 2005) provide the crew with housekeeping support. Potable water is available for body hygiene while the crew is on the surface of Luna. Additionally, to be consistent with CEV and LSAM from ESAS (2005), the crew may have 5 kg/CM for recreational supplies. Mass for sleep accommodations for LO may be greater than CEV and LSAM due to the overall mission length.

5.2.3 WASTE SUBSYSTEM

The Waste Subsystem provides only rudimentary collection and storage of waste products. The waste suite includes a toilet, pretreatment to stabilize urine, and separate storage volumes for human liquid and solid metabolic wastes and trash. Residual human liquid and solid metabolic wastes will return with the crew and not be left within the LO when the crew departs to comply with international treaty (UN, 1967).

5.2.4 WATER SUBSYSTEM

Within the baseline LO Water Subsystem, urine is processed by vapor compression distillation (VCD). The brine is sent to the Waste Subsystem. All grey water, including hygiene water, effluent from VCD, and condensate from dehumidification, is processed through a primary water processor. This primary water processor employs multifiltration (MF), a volatile removal assembly (VRA), phase separators, and ion exchange (IX). A process control water quality monitor provides water quality

[87] A tighter cabin leakage requirement, per BVAD (2004), is 0.00224 kg/d of gas lost. For a long-duration facility such as LO, this may be a more reasonable value to minimize costs associated with supplying atmospheric gases.

assurance. While overall efficiency is high, above 95%, many expendable items, such as filter cartridges, are used. Water, to replenish losses, is supplied in tanks as water.

5.2.5 CREW EXTERNAL INTERFACE

See Section 2.4.3 for a description of crewmembers.

5.2.6 EXTRAVEHICULAR ACTIVITY SUPPORT EXTERNAL INTERFACE

According to ESAS (2005), the free airlock (A/L) internal volume within the LSAM is 5.1 m^3. While an airlock designed for LO may differ, the LSAM airlock provides a representative value for a comparable structure in LO. BVAD (2004) provides usage estimates based upon current EVA technology. For the LO life support architecture using current technology, lithium hydroxide (LiOH) cartridges remove carbon dioxide from the extravehicular mobility unit (EMU) atmosphere. The cartridges themselves are a consumable normally attributable to the extravehicular activities system and not to the life support system.

5.2.7 FOOD EXTERNAL INTERFACE

Food is provided as individual entrées in the LO architecture using current technologies. This diet relies on a variety of ambient-temperature storage (AS) foods. For the design case, this approach supplies 14.40 MJ/CM-d of metabolic energy for intravehicular activities. Employing Levri (2003) and assuming the Shuttle Training Menu as the applicable basis, the design-case metabolic energy corresponds to 1.397 kg/CM-d of food overall. The food mass, as-shipped, is 0.592 kg/CM-d moisture, or 42%, and 0.805 kg/CM-d dry food. An additional 0.321 kg/CM-d of disposable packaging directly protects the food, and specialized food-storage structure, or locker, adds an additional 0.421 kg/CM-d. [88] Assuming the crewmembers attempt to eat all of the consumable content within the food packages, about 0.076 kg/CM-d of hydrated food will adhere to the packaging when it is designated as trash. The corresponding oxygen consumption is 0.986 kg/CM-d, with carbon dioxide production of 1.182 kg/CM-d. [89] Supporting technology includes an undefined heating unit similar in size to a microwave oven.

For days with extravehicular activities, the design case requires additional food (Lane, *et al.*, 1996). Specifically, this approach supplies 16.49 MJ/CM-d of metabolic energy to a 95th percentile male for both intravehicular and extravehicular activities. Employing Levri (2003) and assuming the Shuttle Training Menu as the applicable basis, the design-case metabolic energy corresponds to 1.600 kg/CM-d of food overall. The food mass, as-shipped, is 0.678 kg/CM-d moisture, or 42%, and 0.922 kg/CM-d dry food. An additional 0.368 kg/CM-d of disposable packaging directly protects the food, and specialized food-storage structure, or locker, adds an additional 0.483 kg/CM-d. Assuming the crewmembers attempt to eat all of the consumable content within the food packages, about 0.088 kg/CM-d of hydrated food will adhere to the packaging when it is designated as trash. The corresponding oxygen consumption is 1.130 kg/CM-d, with carbon dioxide production of 1.353 kg/CM-d. [90]

5.2.8 IN-SITU RESOURCE UTILIZATION EXTERNAL INTERFACE

The LO life support system using current technologies does not use in-situ resources.

5.2.9 POWER EXTERNAL INTERFACE

For a near-term mission to a Lunar Pole or the Lunar Equator, sunlight is an available resource. Thus, the baseline LO architecture uses solar photovoltaic cells for power generation and regenerable fuel

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88 This value does not include secondary structure, such as racks. Rather, this value describes lockers.

89 For a metabolic intake of 7.95 MJ/CM-d, Levri (2003) estimates 0.771 kg/CM-d of food mass overall, as-shipped, with 0.326 kg/CM-d of moisture and 0.445 kg/CM-d of dry food. To contain this food, packing adds 0.177 kg/CM-d and the locker adds another 0.233 kg/CM-d. 0.042 kg/CM-d of rehydrated food adheres to the packaging and is wasted. The corresponding oxygen consumption is 0.545 kg/CM-d, with carbon dioxide production of 0.652 kg/CM-d.

90 For a metabolic intake of 10.04 MJ/CM-d, which corresponds to a 5th percentile female for intravehicular and extravehicular activities, Levri (2003) estimates 0.974 kg/CM-d of food mass overall, as-shipped, with 0.412 kg/CM-d of moisture and 0.562 kg/CM-d of dry food. To contain this food, packing adds 0.224 kg/CM-d and the locker adds another 0.294 kg/CM-d. 0.053 kg/CM-d of rehydrated food adheres to the packaging and is wasted. The corresponding oxygen consumption is 0.688 kg/CM-d, with carbon dioxide production of 0.824 kg/CM-d.

cells for energy storage. Based on ESAS (2005), several possible assumptions lead to a family of estimates for the mission architecture here. For an equatorial site, solar power generation with regenerable fuel cells lead to infrastructure estimates for 25 kW_e-power plants of 632.0 to 746.2 kg/kW_e. The first value assumes cryogenic storage for all fuel-cell reactants, while the second value assumes high-pressure storage for the fuel-cell reactants. For a base located at the South Pole on the North Rim of Shackleton Crater, values of 274.1 to 359.4 kg/kW_e are appropriate. Again, the first value assumes cryogenic storage for all fuel-cell reactants, while the second value assumes high-pressure storage for the fuel-cell reactants. [91]

Finally, actual power generation for the LO during dormancy, especially initial dormancy, is undefined. Power generation while dormant on Luna, especially after an initial crew visits, will likely be similar to the options presented above. In like manner, estimates for power generation during transit might be based upon PEM fuel cells, but overall power requirements during transit are not known at this time.

5.2.10 RADIATION PROTECTION EXTERNAL INTERFACE

The baseline LO life support system architecture has no interchange with the Radiation Protection External Interface. Rather, any radiation protection is provided by dedicated mass, such as polyethylene, integrated into the vehicle structure, and undedicated mass associated with vehicle hardware arranged about the periphery of the crew cabin.

5.2.11 THERMAL EXTERNAL INTERFACE

ESAS (2005) says nothing about the LO thermal control system. Thus, estimates here are derived based upon the values above describing the thermal environment, Section 2.5.3, with a few additional assumptions. In particular, the radiators are sized assuming a 10-mil silver Teflon surface coating with a 10-year end-of-life and an overall mass per surface area of 3.5 kg/m^2. The thermal transport system relies on two loops pumping a single-phase working fluid of 60% propylene glycol with 40% water. Finally, 90% of the thermal load acquisition is via coldplates (CPs) with the remaining 10% acquired via a condensing heat exchanger (CHX). These assumptions are fairly consistent with those listed in ESAS (2005) for the thermal control systems of CEV and LSAM.

For an equatorial site with horizontal radiators, which are likely deployed on the lunar surface near the LO crew habitat, [92] the estimated Thermal External Interface mass is 1,404.6 kg with a power consumption of 0.234 kW_e and an internal volume of 0.123 m^3. [93] Assuming the minimum power-mass penalty above for an equatorial site with the volume penalty below, the overall equivalent mass is 1,564.7 kg with the assumptions listed here. Assuming all input power plus the average crew metabolic load eventually must be rejected as waste heat, the overall LO infrastructure penalty is 61.4 kg/kW_{th}.

For a polar site with horizontal radiators, which, again, are likely deployed on the lunar surface near the LO crew habitat, [94] the estimated Thermal External Interface mass is 750.5 kg with a power consumption of 0.124 kW_e and an internal volume of 0.223 m^3. Assuming the minimum power-mass penalty above for a South Polar site on the rim of Shackleton Crater with the volume penalty below, the overall equivalent mass is 806.7 kg with the assumptions listed here. Assuming all input power plus the average crew metabolic load eventually must be rejected as waste heat, the overall LO infrastructure penalty is 31.6 kg/kW_{th}.

Finally, for a polar site with vertical radiators, which may be body-mounted units affixed to the hull of the LO crew habitat, the estimated Thermal External Interface mass is 891.8 kg with a power consumption of 0.148 kW_e and an internal volume of 0.189 m^3. Assuming again the minimum power-mass penalty above for a South Polar site on the rim of Shackleton Crater with the volume penalty below, the overall equivalent mass is 951.3 kg with the listed assumptions. Assuming all input power plus the average

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91 Assuming nuclear power generation, based upon concepts from the SP-100 Program, an alternate power-mass penalty is 226 kg/kW_e for a nuclear reactor with shielding on a mobile cart (BVAD, 2004).

92 Depending on the overall size and complexity of the radiators, the crew may be asked to help deploy the radiator panels at activation.

93 Because equivalent system mass here considers only volume inside the pressure shell, most of the Thermal External Interface hardware volume is correctly omitted from this calculation. Certainly all of the this vehicle’s volume must be contained within the appropriate launch shroud, but the infrastructure value associated with such volume will be much less than for pressurized volume, so it is excluded from ESM calculations even though actual mass and power are included.

94 Depending on the overall size and complexity of the radiators, the crew may be asked to help deploy the radiator panels at activation.

crew metabolic load eventually must be rejected as waste heat, the overall LO infrastructure penalty is 37.3 kg/kW_{th}.

5.2.12 VEHICLE STRUCTURE

While many structural arrangements are possible for the LO, near-term architecture similar to ISS is highly possible. BVAD (2004) lists 66.7 kg/m^3 as the volume-mass penalty associated with an ISS module shell. Because LO will operate outside of the Van Allen Belts, heavier radiation protection than is inherent in an ISS module structure is required. Assuming a layer of polyethylene inside the cabin hull equivalent to 50 kg/m^2, as recommended within Robertson and Geffre (2004), the additional radiation protection adds 59.1 kg/m^3 to the volume mass penalty. Thus, the overall volume-mass penalty is 125.8 kg/m^3 for the baseline LO. Assuming the polyethylene radiation protection can be integrated into the vehicle primary structure such that it provides some structural integrity to the module shell, achieving on average about a 20% reduction in the composite wall, a value of about 100 kg/m^3 would be appropriate.

5.2.13 LOCATION FACTORS

To date, sources detailing the information necessary to compute location factors for the LO are unknown. However, as a first approximation, the values associated with the LSAM Descent Stage might be appropriate approximations. See Section 4.2.13 for details.

5.3 CONTINGENCY AND CONTINGENCY RESPONSE

While the functionality above outlines a single-string life support system using current technologies, an actual flight-rated life support system is robust, with inherent capability to handle contingencies. HRRSS (2005) identifies current requirements for a human-rated spacecraft. The comments below mention two related aspects of an actual human-rated life support system architecture design: contingencies and responding to contingencies.

5.3.1 CONTINGENCIES

HRRSS (2005) states, under paragraph 3.1.1, that "Space systems shall be designed so that no two failures result in crew or passenger fatality or permanent disability (Requirement 34419)." [95] This requirement applies at all levels of a human-rated vehicle. While actual hardware failure modes are often unknown, most hardware may fail. Thus, a life support system architecture should be designed such that no two failures lead to overall failure of the life support system in all flight modes when the crew is present. For the LO crew habitat, the crew is present only while the vehicle is stationary on the lunar surface, although there are situations throughout the surface mission when the crew would not be able to respond immediately to an on-board component failure.

[95] Paragraph 3.1.2 allows specific exceptions to paragraph 3.1.1. See HRRSS (2005) for details.

5.3.2 CONTINGENCY RESPONSE

The current mission architecture for this lunar mission provides for LO and lunar surface contingencies by allowing the crew to abort in the LSAM to the CEV at any time during the surface phase, so no internal contingency is specified for the LO. However, assuming the crew must depend solely upon the LO during a contingency, a likely contingency duration would be no more than 14 days, threshold, or 10 days, objective. Therefore, any life support system architecture should assure all necessary life-support functions for 14 days, threshold, or 10 days, objective, even if the failure leading to the contingency situation disables some or all regenerative life support hardware and/or temporarily prevents an abort to the CEV using the LSAM. Assume that by the end of a 14-day, threshold, or 10-day, objective, contingency period, a contingency or rescue mission, using the capability required by CTS0405G (Lembeck, 2005a), will provide other means to support the crew. Also note that during contingency situations certain nominal crew functions, such as full-body cleansing or nominal EVA operations, may be curtailed or eliminated.

As a practical measure, ESAS (2005), within the mass estimates, includes one full-cabin repressurization for contingency situations for CEV. In like manner, one full-cabin repressurization should be included for LO. Finally, in some studies, NASA analysts carry a second cabin repressurization to account for gases lost due to normal leakage over the mission. [96]

[96] Note: Total mission equivalent masses should ***not*** include both a second cabin repressurization and make-up gases for leakage because both of these approaches are designed to account for gas losses due to leakage.

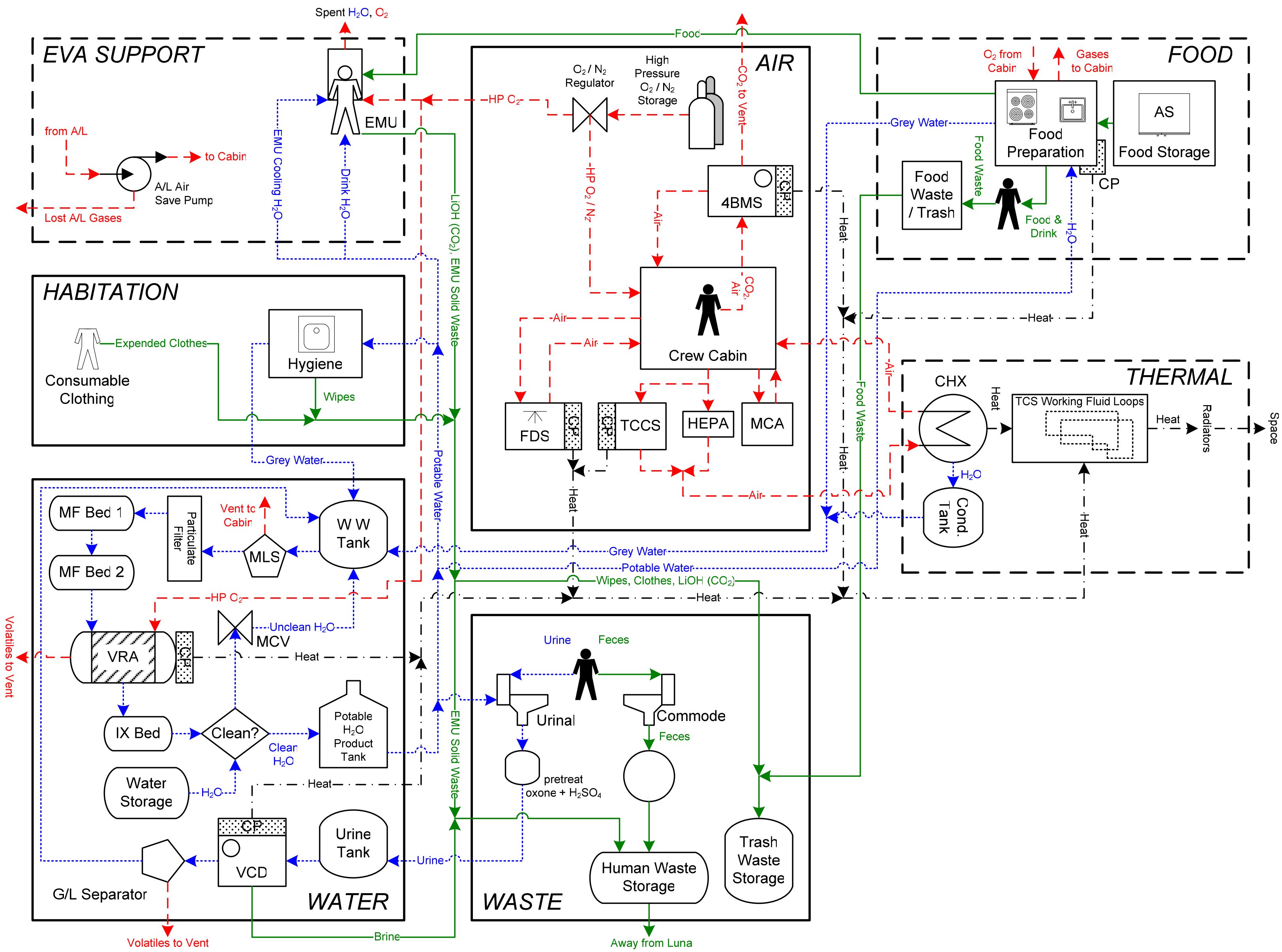

Figure 5.1 Lunar Outpost crew habitat life support system using current technologies.

6 SUMMARY OF VALUES

Table 6.1 summarizes the values for this architecture for each of the mission vehicles in Section 2, Section 3, Section 4, and Section 5.

Table 6.1 Summary of Characteristic Values for Lunar Architecture

Parameter	Units	CEV	LSAM	LO
Lunar Surface Site Layout				
Landing Accuracy	m	n/a	≤100	≤100
Mission Duration				
Permanent Lunar Base Mission				
Overall Vehicle Duration	d/crew	200 [97]	365	181 [98]
Crewed Vehicle Duration	d/crew	18	5	181 [99]
Crewed Duration with Two Crews	d/crew	n/a	n/a	8 [100]
Dormant Vehicle Duration	d/crew	182 [101]	360	0 [102]
Martian Exploration Mission Rehearsal				
Overall Vehicle Duration	d/mission	120	106	146
Crewed Vehicle Duration	d/mission	18	5	101
Dormant Vehicle Duration	d/mission	102	101	45
Crew Size				
Crew Size	CM	4	4	4 [103]
Crewmember Characteristics				
95th Percentile Male (Design Case)				
Mass	kg	98.5	98.5	98.5
Metabolic Energy	MJ/CM-d	14.40	14.40	14.40
Additional Energy for EVA	MJ/CM-d	n/a	2.09	2.09
5th Percentile Female [104]				
Mass	kg	41.0	41.0	41.0
Metabolic Energy	MJ/CM-d	7.95	7.95	7.95
Additional Energy for EVA	MJ/CM-d	n/a	2.09	2.09
Solar Insolation at Sub-Solar Point				
Low-Earth Orbit (LEO)				
Average Insolation	W/m²	1,367	1,367	n/a
Maximum Insolation	W/m²	1,414	1,414	n/a
Minimum Insolation	W/m²	1,322	1,322	n/a
Low-Lunar Orbit (LLO) / Lunar Surface				
Average Insolation	W/m²	1,367	1,367	1,367
Maximum Insolation	W/m²	1,422	1,422	1,422
Minimum Insolation	W/m²	1,315	1,315	1,315

97 The CEV for the first crew will have an overall mission duration of 61 days.
98 The first crew surface mission is only 42 days.
99 The first crew surface mission is only 42 days.
100 The overlap duration is only 4 days for the first crew because the LO is empty when the first crew arrives.
101 The first crew will leave CEV dormant in orbit for 43 days.
102 The LO may be dormant up to 45 days before the first crew arrives.
103 Or 8 CM when two crew occupy LO during the handoff period.
104 While a 95th percentile male, based on the NASA Astronaut Corps selection criteria, is the design case, all vehicle designs should not preclude 5th percentile females.

Parameter	**Units**	**CEV**	**LSAM**	**LO**
Environmental Lighting				
Complete Lunar Day	h	n/a	708.7	708.7
Lunar Equator				
Lighted Duration	h	n/a	354.3	354.3
Dark Duration	h	n/a	354.4	354.4
Lunar Pole				
Minimum Lighted Duration	h	n/a	496.1	496.1
Maximum Dark Duration	h	n/a	212.6	212.6
Lunar Surface Temperature				
Equatorial: Maximum	K	n/a	384	384
Equatorial: Minimum	K	n/a	102	102
Pole: Maximum	K	n/a	233	233
Pole: Minimum	K	n/a	213	213
Pole: In Perpetual Shadow	K	n/a	<100	<100
Lunar Surface Bolometric Normal Albedo				
Average Albedo, Near Side	--	0.12	0.12	0.12
Maximum Albedo, Near Side	--	0.20	0.20	0.20
Minimum Albedo, Near Side	--	0.067	0.067	0.067
Average Albedo, Far Side	--	0.15	0.15	0.15
Parameters for Life Support Subsystems *Air* [105]				
Maximum Overall Cabin Pressure	kPa	101.3	70.3	55.2
Partial Pressure of Oxygen	kPa	21.3	18.6	17.7
Minimum Overall Cabin Pressure	kPa	70.3	55.2	55.2
Partial Pressure of Oxygen	kPa	18.6	17.7	17.7
Minimum Partial Pressure of Oxygen	kPa	16.0	16.0	16.0
Maximum Partial Pressure of Carbon Dioxide	kPa	0.71	0.71	0.71
Maximum Cabin Air Temperature	K	300	300	300
Minimum Cabin Air Temperature	K	291	291	291
Maximum Cabin Dew Point	K	289	289	289
Minimum Cabin Dew Point	K	278	278	278
Maximum Ventilation Velocity	m/s	0.20	0.20	0.20
Minimum Ventilation Velocity	m/s	0.079	0.079	0.079
Cabin Atmospheric Leakage Rate	kg/d	0.15	0.15	0.15
Habitation				
Shall the crew be able to perform hand and body washing?	--	Yes	Yes	Yes
Shall the crew have clothing?	--	Yes	Yes	Yes
Clean Clothing Supply	kg/CM-d	0.46	0.46	0.46
Disposable Wipes	kg/CM-d	0.15	0.15	0.15
Recreational Supplies	kg/CM	5	5	5
Sleep Accommodations	kg/CM	2.3	2.3	Undefined

[105] These are nominal or set-point values for cabin atmospheric parameters. See text for variations.

Parameter	Units	CEV	LSAM	LO
Waste				
Shall the vehicle provide odor control?	--	Yes	Yes	Yes
Shall the vehicle provide trash stowage?	--	Yes	Yes	Yes
Shall the vehicle provide accessible trash collection?	--	Yes	Yes	Yes
Shall the vehicle collect disposable wipes for urination and defecation?	--	Yes	Yes	Yes
Urine Collection				
Volume	m^3/mission	0.118	0.052	1.46
Rate of Collection	m^3/h	$\leq$0.006	$\leq$0.004	$\leq$0.004
Fecal Collection				
Rate of Collection, Mass	kg/CM-d	0.150	0.150	0.150
Rate of Collection, Volume	m^3/CM-d	0.000150	0.000150	0.000150
Rate of Diarrheal Discharge	m^3/CM-d	0.004	0.004	0.004
Can human metabolic wastes be left on or impact the Moon?	--	No	No	No
Water				
Potable Water				
Drinking Water	kg/CM-d	2.5	2.5	2.5
Drinking Water following Landing	kg/CM	4.5	n/a	n/a
Hygiene Water	kg/CM-d	0.5	2.0	5.45
Water Temperature				
Hot Water	K	347.0	347.0	347.0
Cold Water	K	279.0	279.0	279.0
Body Cleansing	K	310.9	310.9	310.9
Parameters for Life Support External Interfaces				
Extravehicular Activity (EVA) Support				
Is EVA part of the nominal mission?	--	No	Yes	Yes
Is EVA part of the contingency?	--	Yes	Yes	Yes
Airlock				
Free Volume	m^3	n/a	5.1	5.1 [106]
Ullage Losses	%	100	10	10
Nominal EVA Sortie Values				
Duration per EVA Sortie	h/EVA	n/a	8	8
Personnel per EVA Sortie	CM/EVA	4	2	2
Nominal EVA Sorties				
Overall	CM-d_{EVA}	n/a	12	214 [107]
Not Supported by this Vehicle [108]	CM-d_{EVA}	n/a	4	8
Exploration Sorties	CM-d_{EVA}	n/a	0	202 [109]
Logistics Support Sorties	CM-d_{EVA}	n/a	12	12

106 Assumed based on the LSAM airlock.

107 This value applies to an 181-day surface mission; for a 42-day surface mission, there are 34 CM-d_{EVA} overall.

108 The equivalent days of EVA listed here use consumables from another vehicle. They are included here to allow computation of airlock cycles.

109 This value applies to an 181-day surface mission; for a 42-day surface mission, there are 22 CM-d_{EVA} for exploration.

Parameter *Food*	**Units**	**CEV**	**LSAM**	**LO**
Shall the vehicle prevent cross-contamination between food preparation and hygiene areas?	--	Yes	Yes	Yes
Shall the vehicle prevent cross-contamination between food preparation and body waste management areas?	--	Yes	Yes	Yes
Shall the vehicle prevent cross-contamination between food preparation and EVA support areas?	--	n/a	Yes	Yes
Shall the vehicle allow rehydration of food using hot and/or cold potable water?		Yes	Yes	Yes
Duration for the crew to prepare a meal	minutes	30	30	30
Food for 95th Percentile Male (IVA only)				
Metabolic Energy, As-Shipped	MJ/CM-d	14.40	14.40	14.40
Overall Food Mass, As-Shipped	kg/CM-d	1.397	1.397	1.397
Dry Food, As Shipped	kg/CM-d	0.805	0.805	0.805
Moisture, As-Shipped	kg/CM-d	0.592	0.592	0.592
Disposable Packaging, As-Shipped	kg/CM-d	0.321	0.321	0.321
Locker Mass, As-Shipped	kg/CM-d	0.421	0.421	0.421
Wasted Food	kg/CM-d	0.076	0.076	0.076
Oxygen Consumption	kg/CM-d	0.986	0.986	0.986
Carbon Dioxide Evolution	kg/CM-d	1.182	1.182	1.182
Food for 5th Percentile Female (IVA only)				
Metabolic Energy, As-Shipped	MJ/CM-d	7.95	7.95	7.95
Overall Food Mass, As-Shipped	kg/CM-d	0.771	0.771	0.771
Dry Food, As Shipped	kg/CM-d	0.445	0.445	0.445
Moisture, As-Shipped	kg/CM-d	0.326	0.326	0.326
Disposable Packaging, As-Shipped	kg/CM-d	0.177	0.177	0.177
Locker Mass, As-Shipped	kg/CM-d	0.233	0.233	0.233
Wasted Food	kg/CM-d	0.042	0.042	0.042
Oxygen Consumption	kg/CM-d	0.545	0.545	0.545
Carbon Dioxide Evolution	kg/CM-d	0.652	0.652	0.652
Food for 95th Percentile Male (IVA+EVA)				
Metabolic Energy, As-Shipped	MJ/CM-d	n/a	16.49	16.49
Overall Food Mass, As-Shipped	kg/CM-d	n/a	1.600	1.600
Dry Food, As Shipped	kg/CM-d	n/a	0.922	0.922
Moisture, As-Shipped	kg/CM-d	n/a	0.678	0.678
Disposable Packaging, As-Shipped	kg/CM-d	n/a	0.368	0.368
Locker Mass, As-Shipped	kg/CM-d	n/a	0.483	0.483
Wasted Food	kg/CM-d	n/a	0.088	0.088
Oxygen Consumption	kg/CM-d	n/a	1.130	1.130
Carbon Dioxide Evolution	kg/CM-d	n/a	1.353	1.353
Food for 5th Percentile Female (IVA+EVA)				
Metabolic Energy, As-Shipped	MJ/CM-d	n/a	10.04	10.04
Overall Food Mass, As-Shipped	kg/CM-d	n/a	0.974	0.974
Dry Food, As Shipped	kg/CM-d	n/a	0.562	0.562
Moisture, As-Shipped	kg/CM-d	n/a	0.412	0.412
Disposable Packaging, As-Shipped	kg/CM-d	n/a	0.224	0.224
Locker Mass, As-Shipped	kg/CM-d	n/a	0.294	0.294
Wasted Food	kg/CM-d	n/a	0.053	0.053
Oxygen Consumption	kg/CM-d	n/a	0.688	0.688
Carbon Dioxide Evolution	kg/CM-d	n/a	0.824	0.824

Parameter	Units	CEV	LSAM	LO
Power				
Power Supply				
Dormancy Power Level	kW_e		1.5 [110]	3.0 [111]
Nominal Power Level	kW_e	4.5	3.5	25.0
Maximum Power Level	kW_e	6.0	5.0 [112]	undefined
Maximum Peak Power Level	kW_e	8.0	--	undefined
Stored Energy Supply				
Stored Energy, Batteries	kW_eh	13.5	16.0 [113]	undefined
Stored Energy, Fuel Cell Reactants	kW_eh	n/a	1,080 [114]	undefined
Infrastructure Values				
Power-Mass Penalty	kg/kW_e	136.0	166.2	274.1 [115]
Energy-Mass Penalty, Batteries	kg/kW_eh	15.6	12.3	undefined
Energy-Mass Penalty, Reactants	kg/kW_eh	n/a	0.528	undefined
Thermal				
Thermal Loads				
Thermal Load for Sizing	kW_{th}	8.0	8.85	25.5
Overall Cabin Thermal Load	kW_{th}	6.25	6.25	--
Acquired by Cabin Heat Exchanger	kW_{th}	0.75	0.75	2.5
Acquired by Coldplates	kW_{th}	5.5	5.5	23.0
Infrastructure Values				
Acquired by Cabin Heat Exchangers	kg/kW_{th}	49.3	49.3	--
Acquired by Coldplates	kg/kW_{th}	11.8	8.8	--
Thermal Transport	kg/kW_{th}	25.9	15.8	--
Rejection by Radiators	kg/kW_{th}	12.3	8.5	--
Rejection by Consumables	$kg/kW_{th}h$	10.7	6.7	--
Recommended Values for ECLSS [116]	kg/kW_{th} $kg/kW_{th}h$	50.0 10.7	33.1 6.7	31.6[117] --
Vehicle Structure				
Volumes				
Overall Pressurized Volume	m³	29.4	24.6	undefined
Crew Cabin	m³	29.4	16.7	undefined
Airlock	m³	n/a	7.9	undefined
Infrastructure Values				
Volume	kg/m³	133.8	61.7	100.0

[110] Assumed.
[111] Assumed.
[112] This value defines sizing for the power bus and other components that are sensitive to power level.
[113] Ascent stage
[114] Descent stage
[115] Solar power generation with regenerable fuel cells and cryogenic reactants for energy storage (ESAS, 2005). This value assumes a South-Pole site on the North Rim of Shackleton Crater.
[116] See text for underlying assumptions and details.
[117] For a South Polar site on the North Rim of Shackleton Crater with horizontal radiators with a power-mass penalty of 274.1 kg/kW_e.

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8 ABBREVIATIONS AND ACRONYMS

4BMS	four-bed molecular sieve
A/L	airlock
AS	ambient-temperature storage (food)
BVAD	Baseline Values and Assumptions Document
CaLV	Cargo Launch Vehicle
CEV	Crew Exploration Vehicle
CHX	condensing heat exchanger
CLV	Crew Launch Vehicle
CM-d	crewmember-day (*i.e.*, units of crewtime)
CM	crewmember (*i.e.*, units of people)
CO_2	carbon dioxide
CP	coldplate
EAWG	Exploration Atmospheres Working Group
EDS	Earth Departure Stage
ELS	Exploration Life Support (Project)
EMU	extravehicular mobility unit
EOR	Earth orbit rendezvous
ESMD	Exploration Systems Mission Directorate
ESAS	Exploration Systems Architecture Study
EVA	extravehicular activity
°F	degrees Fahrenheit (*i.e.*, English units of temperature)
FDS	fire detection and suppression (system)
ft	feet (*i.e.*, English units of length)
h	hour (*i.e.*, units of time)
H_2O	water
HEPA	high efficiency particulate air (filter)
HP	high pressure (gas)
HRRSS	Human-Rating Requirements for Space Systems
IR	infrared radiation
ISS	International Space Station
IX	ion exchange (beds)
J	Joule (*i.e.*, units of energy)
K	Kelvin (*i.e.*, units of absolute temperature)
kg	kilogram (*i.e.*, units of mass)
kJ	kilo-Joule (*i.e.*, units of energy)
km	kilometer (*i.e.*, units of length)
kPa	kilo-Pascal (*i.e.*, units of pressure)
kW_e	kilo-Watt (electric) (*i.e.*, units of electrical power)
kW_eh	kilo-Watt (electric) hour (*i.e.*, units of electrical energy)
kW_{th}	kilo-Watt (thermal) (*i.e.*, units of thermal power or heat rate)
$kW_{th}h$	kilo-Watt (thermal) hour (*i.e.*, units of thermal energy or heat)
LDRM	Lunar Design Reference Mission
LEO	low-Earth orbit
LiOH	lithium hydroxide (cartridges)
LLO	low-lunar orbit
LO	Lunar Outpost
LOR	lunar orbit rendezvous
LS	Lunar Sourcebook
LSAM	Lunar Surface Access Module
m	meter (*i.e.*, units of length)
m^2	square meter (*i.e.*, units of area)
m^3	cubic meter (*i.e.*, units of volume)
MCA	major constituent analyzer
Metric	Advanced Life Support Research and Technology Development Metric - Fiscal Year 2005
MF	multifiltration (beds)
MJ	mega-Joules (*i.e.*, units of energy)
MSIS	Manned-Systems Integration Standards
N_2	nitrogen
NASA	National Aeronautics and Space Administration
NEDD	Natural Environment Definition for Design
nmi	(international) nautical miles (*i.e.*, English units of length)
O_2	oxygen
OLR	outgoing long-wave radiation
PEM	proton exchange membrane (fuel cell)
PMAD	power management and distribution
psia	pounds (force) per square inch, absolute (*i.e.*, English units of pressure)
SIMA	Systems Integration, Modeling, and Analysis (Sub-Element)
TCCS	trace contaminant control system
UN	United Nations
VCD	vapor compression distillation
VRA	volatile removal assembly
W	Watts (*i.e.*, units of power)